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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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PATTERNS OF PHYLETIC EVOLUTION

BY GEORGE GAYLORD SIMPSON

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OLD METHODS

In the fine optimistic years of early evolutionary paleontology, it became fashionable to draw up genealogical trees for various groups of animals, and especially of mammals, in which the supposed interrelationships of all these creatures were shown by representing the living animals as the ends of twigs and their ancestors through preceding ages as lower and connected parts of the stems, branches, and trunk of the tree of life. It was generally recognized that certain details remained to be filled in, but on the whole the concept was simple and satisfying, and much of the work of that period gives the impression that the missing details were not considered important and that their discovery was considered imminent.

The use of such graphic means of indicating descent is still common, and there are few paleontologists who have not constructed some sort

of phyletic tree, either in words or in an actual diagram. However, a cynical note has crept in, and phylogeny has been subjected to severe criticism, not only by our colleagues, the biologists, but also among paleontologists themselves. As almost every family tree proposed by our predecessors proved, beyond much doubt, to be erroneous in essential features, it is not surprising that much of the old whole-hearted faith in the imminent solution of all such problems has now been lost.

NEW METHODS

It is particularly striking that the old picture of phylogeny as a branching tree has almost entirely disappeared from detailed monographs of special groups and that in its stead appear diagrams suggesting many different lines that are parallel or that diverge but are not connected. A single one of the innumerable instances in recent literature is the phylogeny of the mastodonts as given by Osborn.[1] It has fifteen subfamilies and suggests at least thirty distinct major lines of descent, or independent phyla. These phyla are essentially disconnected and, as far as that eminent authority could determine, none was clearly derived from any other. This example is not the most extreme, nor do I mean to suggest that it is necessarily erroneous, but only that it typifies the tendency toward polyphyletic interpretations. If many of the recent odontological and taxonomic monographs of special groups of mammals are studied, the impression is given that no two mammals, differing in any obvious or significant respect, ever actually had a common ancestor, but that each restricted little phylum has been distinct since the beginning of time. One is almost forced to think that when primordial cells first arose on the planet there were already potentially man-cells, oyster-cells, codfish-cells, ape-cells, and every other distinct sort to correspond to every minor phylum of living things that ever was to arise, and that these various blobs of protoplasm were not on speaking terms. Of course, no one really believes this, and in theory all subscribe to a more rational evolutionary picture, but in practice the common ancestry of two or more phyla is, more often than not, simply listed as hypothetical or undiscovered, and indeed seems to be used more as lip-service to the evolutionary principle than from any deep conviction as to its reality.

These new pictures with their multitudes of independent lines are unquestionably nearer the truth than were the naïve trees formerly in vogue. If the tree symbol has any validity at all, there were incomparably more branches than was supposed even a few years ago, and the tree was one of most peculiar habit, most of the branches springing from

[1] H. F. Osborn: *Proboscidea, a monograph of the discovery, evolution, migration and extinction of the mastodonts and elephants of the world*, Am. Mus. Nat. Hist., Moerithenoidea, Deinothenoidea, Mastodontoidea, vol. 1 (1936).

near the ground and, independent of each other, rising to great heights. On the other hand, it seems that this new conception is now so well established that it may become a habit of mind or a deep prejudice and that the facts will be fitted to it instead of its being adapted to the facts as they are discovered. From the nature of the case, it is well recognized that the chance of our finding the direct, or even the close structural, ancestor of any given species, genus, or other group is small, but it is inconceivable in any present theory as to mammalian history that this chance should not be large enough to be a real factor in our studies. As hundreds and thousands of new fossil mammals are discovered and such a high proportion of them are announced as representing new phyla without known ancestors or descendants, there comes the uneasy feeling that perhaps the pendulum of scientific fashion has swung too far. Certainly we still believe in descent with modification; yet with two really different animals, one older and one younger, before us, it has become difficult to convince ourselves or our colleagues that in this concrete instance one is actually derived from the other.

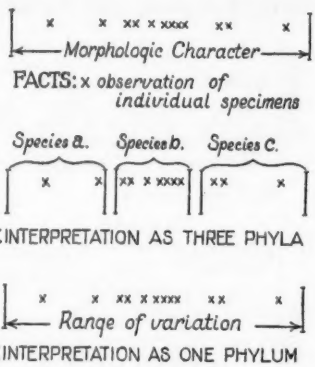

FIGURE 1.—*Two types of phyletic interpretation*

Several similar but varying specimens from one horizon and locality, interpreted as parts of three phyla (A) and as part of a single phylum (B).

This uneasy feeling about the mass psychology of the followers of our science is accentuated when the methods by which these conclusions are reached and the arguments by which they are sustained are scrutinized. Here I may appear in the unfavorable light of a Daniel come to judgment without the precaution of bringing any credentials; I can only say that my criticisms are directed as much against my own work as against that of anyone else, and that I am not satisfied with my progress even in this rather personal field, although I can hope that I have achieved some improvement. In considering the methods used by any student of phylogeny, the natural questions are whether he has really considered all the possible interpretations (consistent with the generally conceded premises of evolutionary paleontology) and whether he has any impelling, impersonal, or objective reason for supporting some particular one of them. As regards an appreciable amount of recent phylogenetic research, the only honest answer to both these questions is "no."

QUESTIONS FOR PHYLOGENETIC RESEARCH

MORPHOLOGY

In order to examine more definitely the bearing of these general considerations on problems of phylogenetic research, several hypothetical and generalized but typical examples of such research may be considered. In the first place, take the familiar, routine task of classifying a number of similar specimens from a limited horizon and locality (Fig. 1). Although postulated as similar, it is certain that their characters cannot be identical, for, as far as has ever been discovered or can be conceived, no two animals identical in character ever existed. There is, then, a range of difference in their morphologic characters, which may be symbolically represented by making a cross for each specimen and placing the crosses at different points on a single horizontal line, although, of course, the differences will really be more complex than such a diagram suggests. It is axiomatic on the basis of current evolutionary philosophy that these individuals are samples from, and that the line on which they are arranged is a cross section of, one or more phyla or lines of descent.

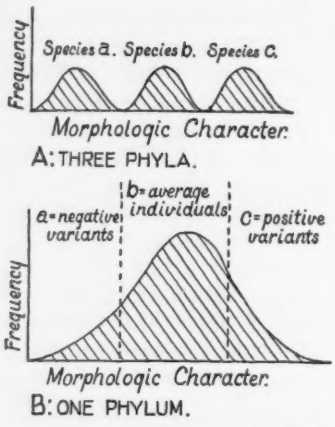

FIGURE 2.—*Frequency distribution criteria*

Generalized types of frequency distributions of distinctive characters of the specimens of Figure 1. (A) Three curves corresponding to three groups, phyla, or species, according to the interpretation of Figure 1A. (B) A single curve corresponding to one phylum, according to interpretation of Figure 1B.

The questions to be answered are: How many phyla are represented and what are their limits. Current methods, which tend to a very polyphyletic view of mammalian descent, might well lead to the recognition of three distinct groups among the specimens at hand; hence, to the conclusion that they represent three distinct phyla (Fig. 1A). The specimens themselves would probably be placed in three species. In the diagram there is no obvious three-fold division, and the lines between the species are placed more or less arbitrarily so as to give each supposed species about the same scope. This is not an unfair representation, for every taxonomist knows that exactly such a division has been made time after time and still is being made daily—for instance, between small-, medium-, and large-sized individuals, all of which intergrade to some extent. On the other hand, the whole group of specimens may belong

to one race or species, and the whole difference between them may be the range of variation within an essentially unified phylum (Fig. 1B).

WHAT IS A SPECIES?

In one form, this problem boils down to the old question as to what is a species (or a subspecies, or a genus). It has been endlessly discussed since Linnaean times and probably will be disputed as long as there are zoölogists. I do not propose to linger long on that aspect of the matter, although it does suggest one example of absurdity that passes almost unchallenged in paleontological research. I was once taught, and I have often heard from other paleontologists or observed as tacitly accepted in their work, that if one specimen is as much as 15 per cent larger than another in any linear dimension, it is safe enough to assume that they belong to different species. The fact is, as everyone who has studied variation should know, that there is hardly any geographic race, let alone any species, in which some variants are not more than 15 per cent larger in some dimensions than are others. On the other hand, a difference in the average dimensions of two groups of individuals may be a perfectly valid and highly significant specific character, even though the difference is considerably less than 15 per cent.

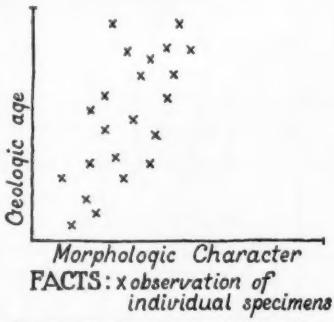

FIGURE 3.—*Sample of similar but varying specimens*
Extending over an appreciable span of geologic time.

The only other point to be made here with regard to this example is that, if the specimens really represent three distinct phyla, there must be some objective difference between them, not as individuals but as groups. Differences between the individual specimens do not in themselves necessarily have any phyletic significance, for two individuals always differ from each other, but, if such varying differences can be shown to characterize and to differentiate groups of individuals, they take on wide meaning. One of the most conclusive ways in which such group characters can be differentiated is by means of frequency distributions (Fig. 2). If the specimens really represent three different groups (here postulated as being phyla), then in some characters they will almost inevitably show separation in a frequency curve with three different modes, or apices. If, on the other hand, only one group is really present, then the frequency distributions will usually show that the supposed three

groups include merely the negative, average, and positive variants within a single natural unit.

It should be emphasized that curves derived from actual data are never so smooth as those shown in the diagram, that double or multiple

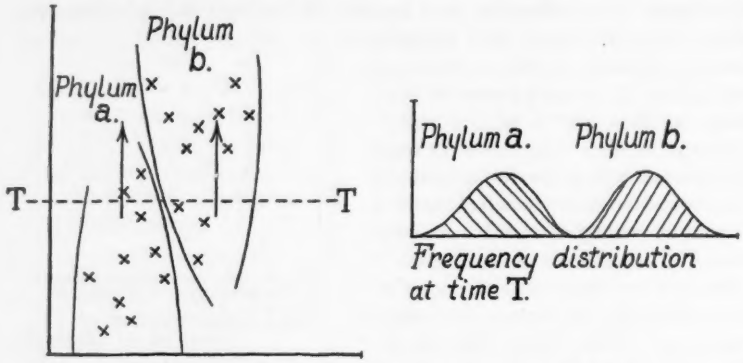

FIGURE 4.—*Data of Figure 3 interpreted as two parallel phyla*
Representing two distinct and parallel phyla, with the type of frequency distribution at any one time, such as T, that would make this interpretation probable.

frequency curves do not always demonstrate phyletic separation, and that there are other difficulties and disabilities in the way of this method. Paleontological research will always require a certain amount of personal judgment; this method is not a universal solution of phyletic problems, but it is a remarkably useful tool, and its almost total neglect in this field is unfortunate.

One rather obvious difficulty is that much research on phylogeny, insofar as it uses the direct data of paleontology, must be based on few, or even on single, specimens. Some of the precise methods, many of the results, and most of the basic logic of the interpretation of frequency distributions are, nevertheless, applicable to small samples and even, strange as it may seem, to unique specimens. This is too complex a subject to discuss further here. Moreover, there are available entirely adequate and even large samples of many fossil mammals. In most institutions, only the one or two best specimens, and those that supplement them, are considered to have any significance and only they are studied with any care. The others are "duplicates," to be discarded, sold, exchanged, or forgotten. Nevertheless, it is only from these duplicates that many basic problems of phylogeny can ever be satisfactorily solved. Paleontological psychology has been to direct attention, to a disabling extent, to the individual specimen, and the number of publications on

fossil mammals in which a suite of specimens has been adequately and correctly studied as representative of a group can almost be counted on the fingers of one hand.

GEOLOGIC AGE

A second example more nearly approximates the usual conditions of phylogenetic research on paleontological materials (Fig. 3). As before,

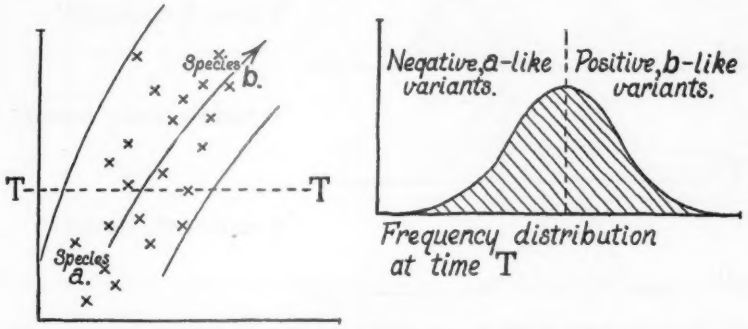

FIGURE 5.—*Data of Figure 3 interpreted as a single phylum*
Representing a single changing phylum, with the type of frequency distribution at any one time, such as T, that would make this interpretation probable.

morphologic differences are symbolized by the horizontal distribution of crosses, representing individual specimens, whereas a second, vertical dimension is introduced to represent the distribution of these specimens in time—that is, their geologic ages.

In this instance, three principal types of phyletic interpretation are possible, and all three should be considered in each case. The first general type of interpretation is to consider them as two or more phyla, perhaps related but essentially independent—that is, not ancestral or descendant. An interpretation of this type is that exemplified as two phyla, partly overlapping in time, evolving in parallel directions, as suggested by the arrows in the diagram (Fig. 4), but separated by certain relatively constant morphological distinctions, symbolized by their relative positions in the diagram. This is now the fashionable interpretation, and it is almost invariably applied by someone, sooner or later, to data that fall more or less into this pattern. Hence, we have the current picture of parallelism as an all but universal phenomenon in mammalian evolution.

If the criterion of frequency distribution can be applied to such cases, a sample of unified age, including parts of both phyla, should, as regards some of its characters, at least, give a curve that is signifi-

cantly bimodal, or two distinct curves. For the sake of simplicity in this and other instances, these curves have been represented as approximately normal. *A priori,* several other types of curves might appear, and the problem might then be complicated even beyond what has already

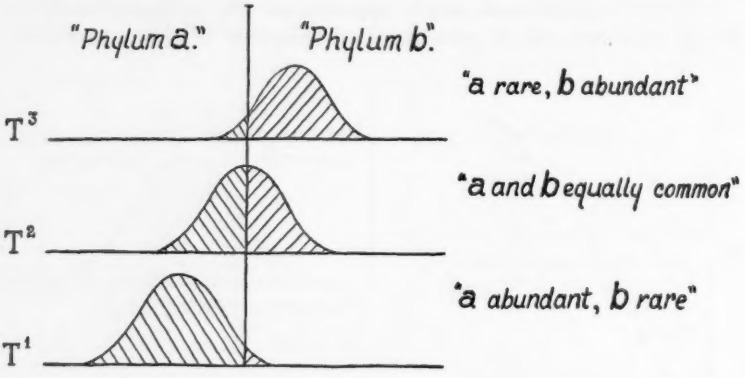

FIGURE 6.—*Artificial dissection of successive frequency distributions pertaining to a single phylum*
Erroneously attributed to two separate phyla.

been suggested. In practice, however, the application of these methods in many different cases to such variates as are commonly used in establishing supposed phyletic distinctions has shown that their frequency distributions almost always approximate the normal curve closely enough to validate the use of constants and methods of analysis based on that curve.

SINGLE PHYLUM OF CHANGING CHARACTER

A second type of interpretation of data of this general pattern is as a single phylum of distinctly changing character (Fig. 5). In this interpretation there is not supposed to be a phylum *a*, the members of which have, for example, smaller horns, and a parallel phylum *b*, with, for the sake of illustration, larger horns, but, instead, a single phylum in which an older species *a* is transformed by mutations in time into a younger species *b* with larger horns. This type of interpretation is so simple and must, in the very nature of things, have been so common in reality that it is surprising to note how seldom it is now invoked. In circumstances as simple as those of larger- and smaller-horned individuals, here employed to facilitate simplicity of verbal expression and diagrammatic exemplification, this more obvious interpretation is, indeed, frequently accepted, but if the conditions are more complex, as they almost always

are in dealing with concrete observations, then the polyphyletic interpretation is at least as likely to be advanced as that of simply monophyly.

If a single phylum be represented, an adequate sample unified as to time will tend to give a single and unimodal frequency curve. Here

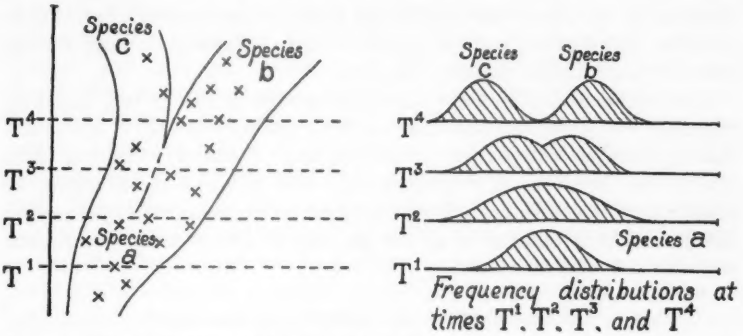

FIGURE 7.—*Data of Figure 3 interpreted as an ancestral stock giving rise to two divergent phyla*

With the types of frequency distributions at successive times, T^1, T^2, T^3, and T^4, that would make this interpretation probable.

again, sight is not lost of the fact that a separation may be observed that is not phyletic but is sexual or is caused by different age groups or some other factor, but these biological considerations must, in any event, be kept clearly in mind and allowance for them may be taken for granted in considering the broader principles of phyletic research.

Actual examples in which a single changing phylum has been interpreted as two parallel phyla are probably common in the literature. I have encountered several cases in which the frequency distributions and other relatively objective criteria show beyond reasonable doubt that this has been done, although these criteria have, as yet, been applied in only a few of the many cases in which I hope they will eventually be used. Particularly prevalent in our literature are interpretations in which two related species (or other groups), *a* and *b*, are said to overlap in time in such a way that first *a* is abundant and *b* rare, then the two are about equally common, then *a* is rare and *b* abundant. This, now a common type of interpretation, involving a pattern of two parallel phyla that replace each other in time by the gradual dwindling of one and increase of the other, should be viewed with profound suspicion unless it is supported by something more substantial than the subjective methods so widespread in such research. In several actual cases carefully investigated, it has been found that the facts are, almost certainly, that a

single phylum is present. The average individuals of an earlier time are considered as of one phylum, *a*, and the average individuals of a later time as of another phylum, *b*. In a sample of intermediate age, variants more resembling the earlier forms are considered as of phylum *a*, and those nearer the later forms are considered as of a distinct phylum *b*, whereas, in fact, they are simply the negative and positive variants in a unified distribution, and the sample is of an intermediate stage linking *a* and *b* into a single phylum (Fig. 6).

It is probable that in some cases the reverse of this is true and that what are really two separate and more or less parallel phyla have mistakenly been interpreted as a single phylum. Certainly, this was often true in earlier work on phylogeny, but now most of these artificially simplified phyla have been dissected; there is considerable evidence that the dissection is tending to go too far and to create many separations that did not exist in nature.

ANCESTRAL STOCK AND SUBSEQUENT BRANCHING

The third principal possibility in interpreting data of this general pattern is that the phyletic history is one of branching (Fig. 7). In such a case, an ancestral species, *a*, gives rise both to a progressive species, *b*, and to a divergent species, *c*, or else the parent stock also continues in more or less unaltered form so that the progressive group *b* is contemporaneous with a conservative group more or less representing its structural ancestry, a common phenomenon in mammalian history and one of great helpfulness in reconstructing phylogeny if the true ancestral group has not been discovered. As drawn, the diagram more nearly approximates a pattern of this latter sort, *c* differing little from *a*, but the general principle would be the same if *c* were quite unlike either *a* or *b*.

The simplest types of successive frequency distribution patterns corresponding to such a history are also shown in the diagram. At an early period an adequate sample would tend to show, as regards many of its variates, a single and approximately normal curve, typical of a single phylum of average variability. Assuming in this simplified example that the splitting of the phylum takes place gradually and by the segregation into two stocks of mutations, which are at first slight and are likely to occur in any member of the parent stock, the next stage in time would tend to show frequency curves still single but exceptionally low and broad, technically platykurtic, corresponding to increased variability or mutability in the race. Still later, as segregation begins to be a visible factor, the curves will tend to be bimodal. Finally, the characters distinguishing the two descendent phyla will give two separate curves.

CONCLUSION

In every case of data of this general type, which is by far the commonest type with which a paleontologist has to deal in drawing up phylogenies, these three general sorts of interpretation are about equally probable *a priori*. Under the best circumstances and applied with proper judgment, the frequency distribution criteria here outlined in their simplest and most generalized form are unquestionably the most conclusive that can be employed. As yet, they are probably directly applicable only to a minority of our problems, although the available data are rapidly increasing. In default of these, there are other criteria nearly as useful, and still others of decreasing value until they approach guesswork, which also has a place in our literature. It would seem desirable to adopt the simplest interpretation, unless there are definite and strong reasons for adopting one more complex. A group may well be considered monophyletic until some contrary probability is established. This is in keeping with sound general principles of research and is also a salutary attitude in view of recent extreme trends in this particular field. As a point of less theoretical but great practical importance, it also tends to impede unnecessary complication of nomenclature and of taxonomy, which is the chief instrument of discussing phylogeny and, however imperfectly, is a means of representing it.

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POSITION, EXTENT, AND STRUCTURAL MAKEUP OF APPALACHIA

BY W. T. THOM, JR.

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1. Configuration of old land surface of a part of Appalachia, and rates of slope of sub-Eocene and sub-Miocene erosion surfaces in Middle Atlantic States ... 316

INTRODUCTION

A few portions of the earth's surface naturally stand out as the most logical places in which to initiate studies aimed at the solution of the major problems of geology, and particularly of such problems as deal with the manner of origin of "geosynclines of sedimentation," with the processes of mountain building, and with the sequences of diastrophic events that characteristically both lead up to, and follow, an "orogenic revolution."

In order to qualify as such a "test area," a region must meet several specifications: It must present an abundance of varied and easily accessible outcrops; it must contain many mountain uplifts, canyon sections, deep wells, and mine workings to provide a notable third-dimensional component to the purely areal picture afforded by lowland outcrops; it must be, at least in part, a region in which the usual geological exploratory techniques have been long and especially intensively applied—thus providing loci of "known geological conditions"—from which new exploratory techniques can be carried outward into less well known and even unknown territory. And finally, a "test region" must provide operating conditions that are simultaneously favorable to successful, convenient,

and inexpensive application of modern geophysical-geological exploratory methods.

Even a brief consideration of the foregoing specifications will suffice to show that one of the best geological-geophysical test areas in the world can be roughly delimited as extending from southwestern New England, on the north, to the Carolinas, on the south, and from Pittsburgh and Knoxville, on the west, to an as-yet-indefinite eastern boundary—lying within the Atlantic Ocean basin, and well beyond the foot of the slope descending from the continental shelf to the ocean floor. For lack of a better descriptive name, the writer has termed this area the "Middle Atlantic States" region, and he suggests that it be considered: First, because of the immediate opportunities it presents for effective integration of stratigraphic-paleontologic, structural-petrologic, paleogeographic-physiographic, and geophysical exploratory methods; and, second, because of the prospect that through such integrated work the position, extent, and structural makeup of the (partly) vanished continent of Appalachia may be determined, thus making known the nature, manner of operation, and time of application of the forces that have deformed the crustal rocks of this "Middle Atlantic States" region within post-Cambrian time.

Because this region is thoroughly familiar to most geologists, and because its general features and regional relationships are so well summarized in various International Geological Congress Guidebooks,[1] it seems both undesirable and unnecessary to repeat here the factual and historical summaries and the bibliographies provided by these guidebooks. For present purposes it will probably be sufficient to recall that the stage has been set for the new exploratory cycle now beginning: First, by more than 100 years of study of the fossiliferous sediments that were derived from Appalachia and were deposited in the geosyncline to the

[1] C. R. Longwell, *et al.: Eastern New York and western New England*, 16th Internat. Geol. Cong., Guidebook 1, Excursion A-1 (1933) 118 pages.

Charles Butts, *et al.: Southern Appalachian region*, 16th Internat. Geol. Cong., Guidebook 3, Excursion A-3 (1933) 94 pages.

D. H. Newland, *et al.: The Paleozoic stratigraphy of New York*, 16th Internat. Geol. Cong., Guidebook 4, Excursion A-4 (1933) 136 pages.

L. W. Stephenson, *et al.: Chesapeake Bay region*, 16th Internat. Geol. Congr., Guidebook 5, Excursion A-5 (1933) 49 pages.

Douglas Johnson, *et al.: Geomorphology of the Central Appalachians*, 16th Internat. Geol. Cong., Guidebook 7, Excursion A-7 (1933) 50 pages.

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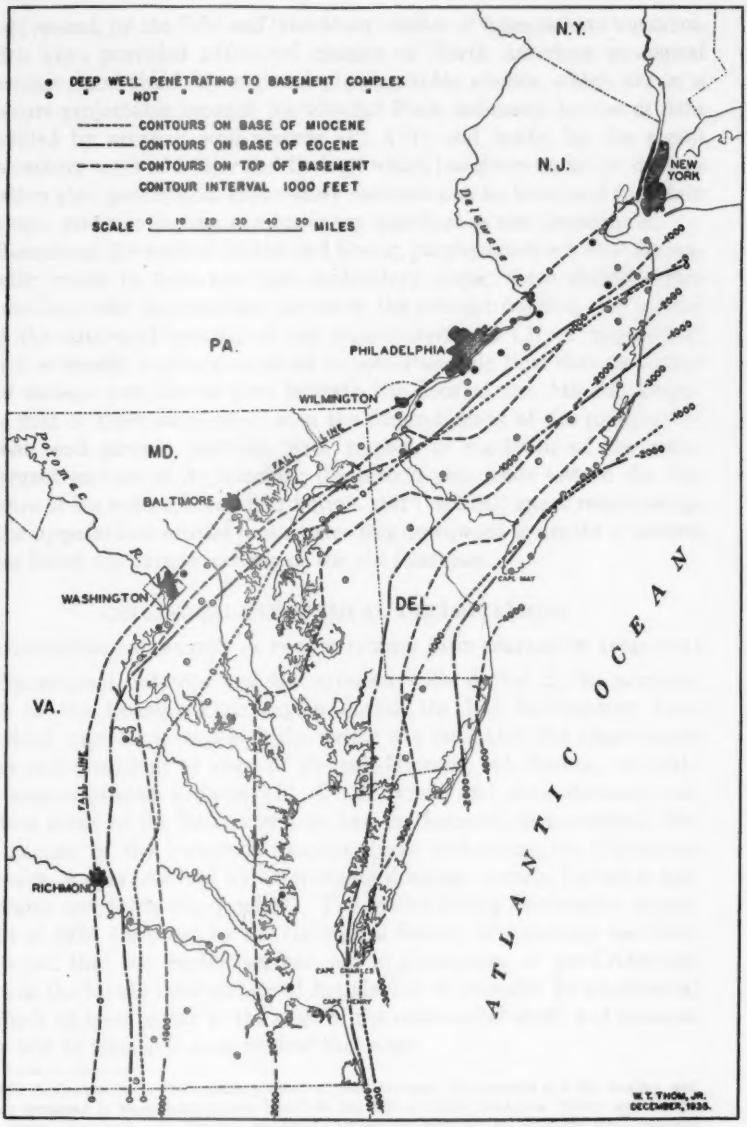
G. H. Chadwick and G. M. Kay: *The Catskill region*, 16th Internat. Geol. Cong., Guidebook 9a, Excursion New York 11 (1933) 25 pages.

G. W. Stose, *et al.: Southern Pennsylvania and Maryland*, 16th Internat. Geol. Cong., Guidebook 10, Excursions B-1, B-2, B-3 (1933) p. 1-26.

Arthur Bevan, *et al.: Northern Virginia*, 16th Internat. Geol. Cong., Guidebook 11, Excursions B-4, B-5, B-6 (1933) 43 pages.

C. W. Cooke: *Southern Maryland*, 16th Internat. Geol. Cong., Guidebook 12, Excursion B-7 (1933) 16 pages.



Configuration of old land surface of a part of Appalachia, and rates of slope of sub-Eocene and sub-Miocene erosion surfaces in Middle Atlantic States

west; second, by the field and laboratory studies of Appalachian tectonics, which have provided additional classics of North American geological literature; and third, by regional physiographic studies, which are in a measure projectable beneath the Coastal Plain sediments by use of data provided by artesian well records (Pl. 1[2]); and lastly, by the recent exploratory work of Miller and Ewing,[3] which has given an initial demonstration that geophysical exploratory methods can be thus used to obtain geologic evidence having revolutionary significance and importance.

Because of the work of Miller and Ewing, geophysicists are now demonstrably ready to take two new exploratory steps; these should suffice to disclose with approximate accuracy the present position, the extent, and the structural makeup of the former continent (?) of Appalachia, which evidently has been so tilted in post-Paleozoic time that its former land surface now lies in part beneath the floor of the Atlantic Ocean. The first of these steps deals with the determination of the topography, extent, and present position, with respect to sea-level, of the once-emergent surface of Appalachia; the second step leads toward the disclosure of the nature, areal distribution, and (vertical) space relationships of the Appalachian crustal rocks, extending downward to depths of several miles below the former surface of the old landmass.

GEOLOGICAL-GEOPHYSICAL DELIMITATIONS

CONFIGURATION AND EXTENT OF PRE-CRETACEOUS LAND SURFACE OF APPALACHIA

Formational outcrops and the artesian wells drilled in the northern part of the Coastal Plain region during the last half-century have provided controls from which the writer has estimated the approximate rates and directions of slope of the sub-Miocene, sub-Eocene, and sub-Cretaceous erosion surfaces (Pl. 1). A recent and more detailed subsurface study of the Baltimore area has, furthermore, demonstrated that the surface of the basement complex, there underlying the Cretaceous deposits, is characterized by an intricate drainage pattern having a considerable and fairly sharp relief.[4] The Miller-Ewing cooperative experiment of 1935 (financed by the Geological Society of America) has demonstrated that the erosion surface, cut in Cretaceous or pre-Cretaceous time on the former land surface of Appalachia, is traceable by geophysical methods at least as far as the edge of the continental shelf, and presumably will be traceable even beyond that edge.

[2] Plate 1 presents the writer's interpretation of data provided by outcrops and by artesian well records contained in many publications, issued by the United States Geological Survey and by the New Jersey, Maryland, and Virginia geological surveys, or provided by open-file data available for consultation in the offices of the three State geological surveys mentioned.

[3] Maurice Ewing, *et al.: Geophysical investigations in the emerged and submerged Atlantic Coastal Plain.* Pt. I, *Methods and results*, Geol. Soc. Am., Pr. for 1934 (1935) p. 75.

[4] E. B. Mathews: *personal communication.*

Therefore, by the joint use of the seismic reflection and refraction techniques in the Coastal Plain region between the Hudson River and Cape Hatteras, it should be possible to determine, first, the degree of precision of these methods as applied to the problems of the region, and, second, the nature of the buried topographic (and structural?) pattern beneath the portion of the Coastal Plain lying between the Fall Line and the strand. When the configuration of the crystalline floor of this area is known with precision, it should be relatively easy to trace this surface seaward by seismic traverses extending across the continental shelf, and it should also be possible, though more difficult, to carry the exploration beyond the continental shelf.

At the outset, it would be desirable to make refraction and reflection traverses both from Lakewood and Philadelphia to Cape May, and thence to Washington and Richmond, and to follow these traverses by several others, run seaward from selected points on the inland margin of the Coastal Plain. The data thus assembled should suffice to disclose the best way to carry on further seismic work on land and at sea.

SUB-SURFACE MAKEUP OF OLD APPALACHIAN LANDMASS

To determine the sub-surface structure and the makeup of the earth's crust within a region, two things are necessary: First, that the areal, petrologic, and structural space relationships be ascertained with essential accuracy, through the use of ordinary geological exploratory methods; and, second, that critical parts of the region be tested by the independent application of at least two, and preferably several, different geophysical methods, responsive to controls exercised by different physical properties of the existent rock bodies. Thus, by using the multiple-approach method and by working from the known to the unknown, one can make positive determination of unknown geologic factors by developing more equations than there are unknowns to be determined.

That a combination of geophysical methods (plus geological interpretation) can be thus used to determine the sub-surface composition and makeup of the old Appalachian landmass is partly indicated by the significant gravitational "picture" provided by Figure 1, and is further indicated by the general experience of those engaged in seismic exploration, plus the recent experimental demonstration by Ewing [5] that quarry blasts can satisfactorily be used as a source of energy for seismic studies. Abundant additional evidence also indicates that different, but equally important, information concerning the nature and space relationships of sub-surface rock bodies can also be obtained through the use of instru-

[5] Maurice Ewing: *personal communication.*

ments responsive to differences in the magnetic properties [6] and electrical conductivity of these different rock bodies.

As starting points for the projected geological-geophysical dissection of the Appalachian landmass, geological maps of a portion of it show

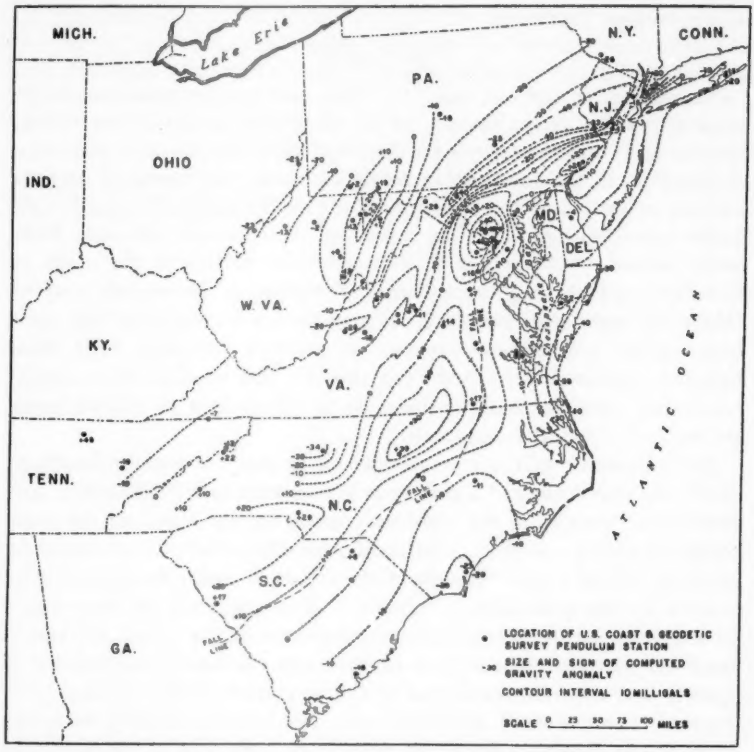


FIGURE 1.—*Local variations in vertical intensity of gravity in Middle Atlantic region*

areal, structural, and petrologic relationships; and a semi-detailed gravimetric map (Fig. 1) shows by iso-anomaly lines the variation in the vertical component of gravity in the Middle Atlantic States region, as determined by the United States Coast and Geodetic Survey.

Figure 1 shows a row of gravitational "highs," increasing in size and decreasing in steepness of horizontal gradient, which extends from Hoboken to Georgia, along a line that gradually diverges westward from

[6] G. R. McCarthy: *Magnetic anomalies and geologic structures of the Carolina Coastal Plain*, Jour. Geol., vol. 44 (1936) p. 396-406.

the Fall Line as it is traced toward the south. On close inspection, it is also evident that another elongate and parallel gravitational "high" is present beneath the eastern edge of the Allegheny plateau in southwestern Pennsylvania, western Maryland, and northeastern West Virginia, and that a similar feature is probably present on the same trend in northeastern Tennessee.

CONCLUSION

Considering, on the one hand, the form and relative positions of the areas of positive anomalies and, on the other, the geology of the region, it seems clear that the surface gravitational variations are here relatively independent of the topographic configuration of the basement surface and are indicative of the presence of local and abnormally heavy rock bodies imbedded just below the surface of the basement complex. Such heavy masses would appear to lie nearest the surface of the earth at Hoboken, and at progressively greater depths as the eastern zone of "highs" is traced southwestward. It may further be suggested that these heavy bodies are intrusive masses. In order to determine what these intrusive masses may be, how deep they lie, and what geologic significance they have, it would be desirable to collect data as follows, using the method of multiple approach:

First, intensive seismic traverses should be made in various directions across the gravitational "highs" near Washington and Philadelphia, and across the "trough" to the northwest, using quarry blasts as the main source of energy. Second, additional pendulum observations should be made at critical points throughout the region, in order to obtain better control for the gravitational "picture." These primary stations should be connected by second-order observations intended to reveal and record both the variation in direction of the local horizontal components of gravity and the local variations of the magnitude of the vertical component. Third, a study should be made, and extended as may be necessary, of the existing information concerning variations in the local terrestrial magnetic fields and in the earth's electrical properties, along selected profiles from the Allegheny front to the Atlantic coast.

By comparing the results thus yielded by two or more geophysical methods in any area where the surface structure and composition of the crustal rocks are geologically known, accurate geological interpretations of the geophysical data should be possible, both downward and laterally. Moreover, by thus using the emergent western portion of Appalachia as a "calibration area," it would certainly be possible to learn much that is of prime importance in regard to the extent, the physical makeup, and the tectonic history and relationships of this old

landmass, which once stood relatively high above sea-level, and since has been faulted, warped downward, and extensively submerged.

Such an advance in knowledge would substitute fact for speculation in many of the most important fields of geological thought and would correspondingly help to speed the opening of the new era of geological-geophysical exploration, which promises to reveal not only the areal geology of the sub-oceanic areas, but also the essential facts regarding the thickness, composition, and dynamic properties and behavior of the earth's crust as a whole.

PRINCETON UNIVERSITY, PRINCETON, N. J.
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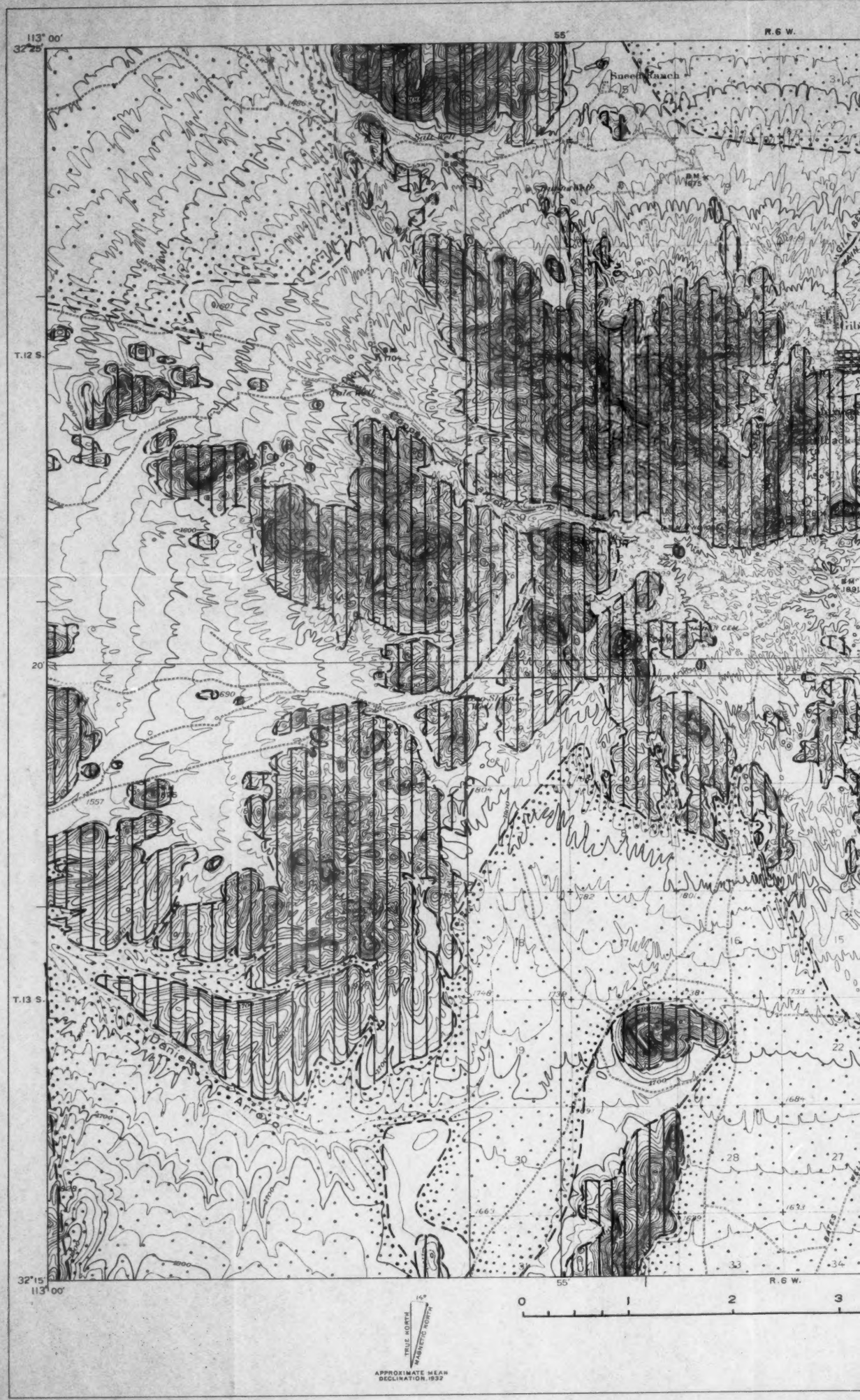
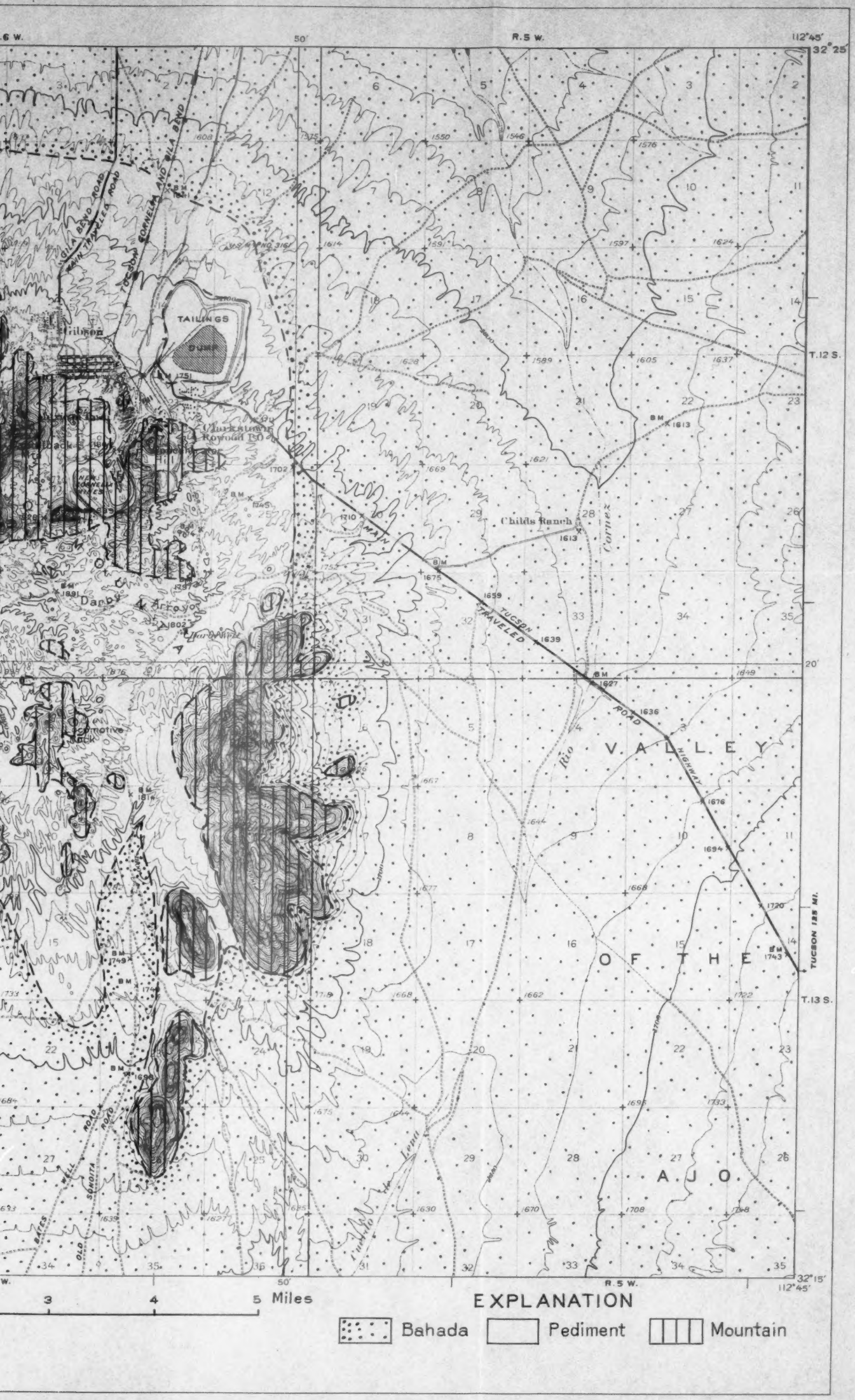


PHYSIOGRAPHIC DIVISIONS OF THE LITTLE AJO MOUN


6 W.
50'
R.5 W.
112°45'
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T.12 S.
T.13 S.
GILA BEND ROAD
SAN TIMOTEO
TUCSON GUNNELLA AND GILA BEND ROAD
TAILINGS
Dump
Childs Ranch
Darby Arroyo
Locomotive Creek
TUCSON TRAVELED
ROAD
HIGHWAY
TUCSON 128 MI.
V A L L E Y
O F T H E
A J O
Cornez
Rio
Lomas
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Lomas

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PHYSIOGRAPHY OF THE AJO REGION, ARIZONA

BY JAMES GILLULY

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INTRODUCTION

Ajo lies in the Papago country of southwestern Arizona, in the Sonoran desert section[1] of the Basin and Range province (Fig. 1). The region, which displays a wide variety of topographic forms, offers unusual opportunity for study to those interested in the physiography of arid regions because the United States Geological Survey has completed topographic maps, one of the Ajo quadrangle on the scale of 1 : 48,000, and one of a few square miles in the mining area near Ajo on the scale of 1 : 12,000.

The Ajo quadrangle includes the small mountain masses of the Little

[1] N. M. Fenneman, *et al.: Physical divisions of the United States*, U. S. Geol. Surv. map (1930).

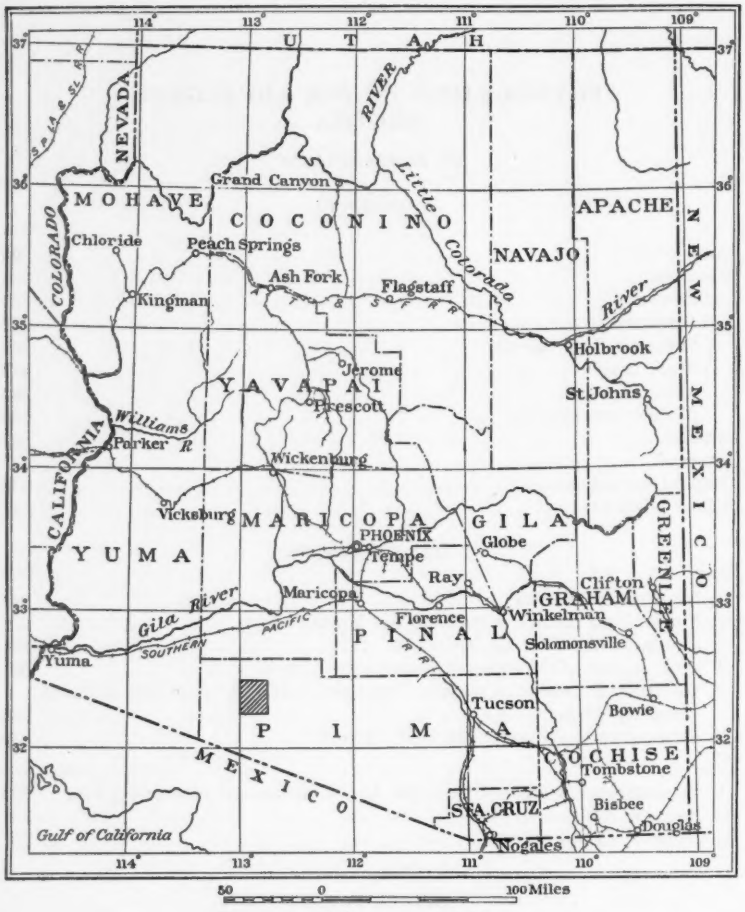

FIGURE 1.—*Index map of Arizona*

Ajo Mountains, Childs Mountain, and part of the Batamote Mountains. Much of the area is occupied by desert plains, of which the largest is the Valley of the Ajo. Altitudes range from 1,150 to 3,200 feet. Local relief is moderate and only exceptionally reaches 1,000 feet in a square mile. The climate is arid, with annual rainfall of about 10 inches and with low humidity. There are no permanent streams, but the drainage is, nevertheless, external.

The rocks of the Ajo region include injection gneiss, granitic gneiss,

massive quartz monzonite, lavas of several ages, fanglomerate, and tuff. The bedrock structure is dominated by block faults, several of which have demonstrable displacement of several thousand feet. None of these faults is directly represented in the topography. Several are now marked by obsequent fault-line scarps (Pl. 3, fig. 2). The present topographic features are, therefore, the products of desert erosion and sedimentation acting upon a bedrock that is heterogeneous both horizontally and in altitude.

The surface forms of the quadrangle, like those of the Sonoran desert section as a whole, can be classed in three groups: (1) the mountains, commonly rugged and steep-sided, with either bare rock at the surface or only a thin cover of talus; (2) the pediments, smooth carved-rock plains, which generally border the mountains and are strewn with a thin, but discontinuous, mantle of gravel; and (3) the bahadas, smoothly rounded alluvial aprons, which slope forward into the axes of the "valleys." Of these, the mountains and the pediments are chiefly carved by erosion; the bahadas are chiefly depositional.

The drainage of the Ajo quadrangle is external, as is that of almost the entire Papago country, in which Ajo is centrally located. Although the climate is now arid, and perhaps was formerly still more arid [2] and the present ephemeral streams still less competent, the drainage of the region has been integrated. This can only mean that a long time has elapsed since the major structural disturbances, a conclusion that is supported by several other lines of evidence, both structural and physiographic.

The map of the Ajo quadrangle is one of the few that portrays the topography of pediments in any detail. The writer has, therefore, thought it worth while to attempt to delimit as accurately as possible the areas occupied by mountains, pediments, and bahadas (Pl. 1). Of these, the mountains are relatively sharply marked off from the others, as they commonly maintain their steep slopes to their rather abrupt junctions with the other physiographic divisions. The andesite lava mountains are bordered by talus piles that blend more gently into the bahadas below, with small or no intervening pediments. The boundaries between the rock plains, or pediments, and the alluvial plains, or bahadas, are far less readily mapped. The pediments carry, especially toward their lower borders, a thin mantle of alluvial material; they can be only objectively distinguished from the bahadas by exposures of bedrock in the shallow trenches of the ephemeral streams, which everywhere score the intermont plains. Of course, well records, where available, confirm

[2] Kirk Bryan: *Erosion and sedimentation in the Papago country, Ariz.*, U. S. Geol. Surv., Bull 730 (1922) p. 65.

the distinction, but it is obvious that mapping based on the criterion of the bedrock inliers must favor the alluvium at the expense of the pediments. Nevertheless, to avoid bias in interpreting the position of this boundary, the pediments shown on Plate 1 are drawn no farther "valleyward" than the intermont outcrops of bedrock.

Blackwelder[3] contrasts the form of the pediment with that of the bahada. He says that the pediment is essentially level parallel to the mountain front, whereas the bahada is smoothly undulating in this direction. This contrast probably holds for many of these features but can hardly be used as a basis for detailed mapping, and it is not everywhere a valid criterion. The fine texture of the drainage channels developed on the known pediments is apparently in contrast with the wider spacing of the channels on the bahadas in the Little Ajo region. This contrast, which may be of genetic significance, is not, of course, of any value in mapping; it is obviously so difficult to measure objectively that not much weight should be given it without study in other areas.

MOUNTAINS

The mountains of the quadrangle are of two kinds, differing in their stages of erosion in such a way as to indicate control by their lithology and structure and presumably by their size and altitude. One, the sierra type, is represented by the main mass of the Little Ajo Mountains (Pl. 2, fig. 2; Pl. 3, fig. 3), the Chico Shunie Hills, Black Mountain, and the low hills south and southwest of Black Mountain. All these are in a stage of mature dissection by their canyons and have knifelike ridges and pointed summits. All except Black Mountain and the low hills southwest of it are composed of massive or fissile rocks whose division surfaces stand steeply. The second, mesa, type of mountain is represented by the Childs and the Batamote mountains. The canyons in these mountains are in a youthful stage, and there are broad mesas between the drainage lines, especially in the lower parts of the mountains. The sides of the mountain of the mesa type may be, on the average, a trifle steeper than those of the sierra type. The less advanced stage of dissection of the mesa type of mountain probably reflects the generally flat dip of the lavas, their permeability to water, the fact that they yield large blocks to the talus slopes, and their consequent resistance to erosion as compared with the massive or steeply tilted rocks of the sierras. As the hills and mountains of lava are generally buried in talus for a considerable height (Pl. 3, fig. 2), their slopes cannot recede (while the talus remains) to lesser angles than those at which the talus is in repose. The fact that Black Mountain and the associated lava-capped hills are, nevertheless,

[3] Eliot Blackwelder: *Desert plains*, Jour. Geol., vol. 39 (1931) p. 136-137.

FIGURE 1. "ISLAND MOUNTAINS" OF LATITE LAVA
Near the south edge of the Ajo quadrangle. Pediment in foreground blends imperceptibly with bahada in the middle view, which in turn blends with narrow pediment at the foot of the latite hills. View looking east from southwest corner of section 16, T. 13 S., R. 6 W.

FIGURE 2. DISSECTED PEDIMENT
Near the head of Copper Canyon on the southwest flank of the Little Ajo Mountains. View looking northeast. North Ajo Peak on the right. Note that the pediment in the foreground (which is cut on pre-Cambrian gneiss) extends headward and unites, at Ajo Peak, with the east-sloping pediment of Darby Arroyo, in the gap north of North Ajo Peak. In this area the pediment is dissected to depths of about 40 feet.

SCENES IN AJO QUADRANGLE

FIGURE 1. VIEW LOOKING EAST FROM A POINT NEAR THE SOUTHWEST CORNER OF THE QUADRANGLE
Gravel pavement (1 pebble deep) on the alluvium of Daniels Arroyo (foreground). Isolated andesite butte (middle distance) and Black Mountain (skyline left center).

FIGURE 2. BLACK MOUNTAIN
View looking east from a point about a mile west of Locomotive Rock. The pediment in the foreground is cut on tilted fanglomerate and tuff. In the left foreground and extending toward Locomotive Rock is the divide between the east-flowing Darby Arroyo and the south-flowing drainage. Black Mountain, composed of gently inclined flows of massive andesite, is a down-dropped fault block with respect to Locomotive Rock.

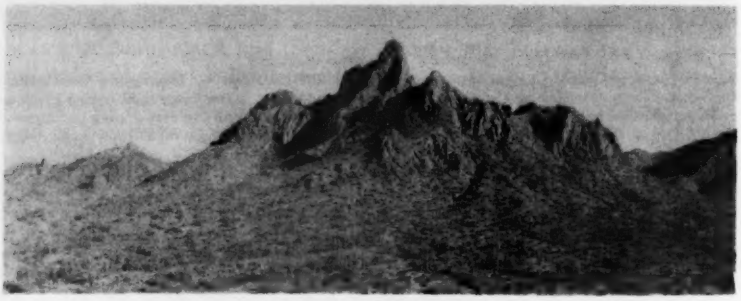

FIGURE 3. NORTH AJO PEAK
As seen from the south. Showing the practically confluent dissected pediments of Darby Arroyo (right) and of Chico Shunie Arroyo (left). The pediments are cut on steeply tilted Tertiary fanglomerate.

SCENES IN AJO QUADRANGLE

sharp-crested sierras suggests that they are carved from small blocks standing at relatively great heights above base level. This is a further expectable consequence of the faults postulated along the east flank of Black Mountain and the other hills.

The slopes on the mountain-sides range from practically vertical cliffs to angles as low as 8 degrees, rarely less. Common slopes on the volcanics are 30 to 45 degrees, on the granitic rocks and gneiss 25 to 35 degrees, and on the fanglomerate 30 to 50 degrees. As pointed out by Bryan,[4] and in conformity with the deductive analysis of Lawson,[5] there is a marked correlation between the size of the fragments of bedrock that mantle a given mountain slope and the declivity of the slope.

Blackwelder[6] has emphasized that talus slopes are far less conspicuous in the southern Basin Range province than in the north. He infers that this is due to the relatively greater efficiency of frost in rifting off blocks to feed the talus in the north and of cloudbursts in removing the blocks in the south. Without questioning the reality of these factors, it is certainly worthy of note that the structural disturbances outlining the several mountain blocks are much younger in the northern Basin Ranges than in the southern. This is evident from the disintegrated drainage of the north as contrasted with the more generally integrated drainage of the south (which is, on the average, more arid), from the topographic expression of fault scarps in the north and commonly of fault-line scarps in the south, and from the presence of pediments in the south and their almost complete absence in the north. It is also supported by the observation of Waibel,[7] that only the high basins peripheral to the Gila remain undrained, all the lower (and more arid) intermont areas being tributary to that stream. All these features accord in pointing to an age difference in the mountains of the two areas, and this in itself may account for the greater prominence of talus in the northern mountains. At any rate, in the Ajo area, talus is found on the physiographically young mountains but is far less conspicuous on the physiographically mature sierras.

PEDIMENTS

DISTRIBUTION

The parts of the relatively smooth but minutely dissected slopes that can be demonstrated to be pediments—that is, to be carved surfaces

[4] Kirk Bryan: *op. cit.*, p. 45.

[5] A. C. Lawson: *The epigene profiles of the desert*, Calif. Univ. Dept. Geol., Bull., vol. 9 (1915) p. 29.

[6] Eliot Blackwelder: *Talus slopes in the Basin Range province* (abstract), Geol. Soc. Am., Pr. for 1934 (1935) p. 317.

[7] Leo Waibel: *Die Inselberglandschaft von Arizona und Sonora*, Zeitschr. Gesell. Erdk. Berlin, Jubilaums Sonderband (1928) p. 80-81.

rather than built surfaces—are limited to certain parts of the mountain bases. How much of their apparent restriction is real and how much is due to dissection in the present subcycle of erosion having been locally too slight to expose the carved bedrock beneath the alluvial veneer, is an open question.

Exposures of planed bedrock are sufficient to demonstrate the existence of a pediment almost entirely around the Little Ajo Mountains and Chico Shunie Hills, except for parts of their southern borders. Pediments extend deep into these mountains, and several from different directions practically coalesce near Ajo Peak (Pl. 2, fig. 2; Pl. 3, fig. 3). Pediments are also known west and northwest of the basalt hills in the southwestern part of T13S, R6W Pl. 2, fig. 1), and narrowly bordering the hills of latite south of Black Mountain. Elsewhere, to judge from exposed bedrock, pediments are either very narrow or absent.

It may be pointed out that a pediment may actually exist along the south side of the Chico Shunie Hills, but the Tertiary conglomerate forming the local bedrock so closely resembles the modern alluvium that the two would be difficult to distinguish except in very favorable exposures. No pediment bordering the Little Ajo Mountains is shown on Plate 1, in sections 8 and 9, T13S, R6W, southeast of Ajo Peak, but the dissection is too slight to expose it, if it were present. That, nevertheless, there may actually be one is suggested by the clear development of a pediment in sections 15 and 10. With these exceptions, the maturely dissected mountains are bordered by pediments; the mesa-like mountains are not. In fact, except for the small areas near the south edge of the map, and north of the tailings dump of the Phelps Dodge concentrator, no demonstrated pediments are carved on the andesites, such as make up Black Mountain. Although there probably was considerable erosion after the uplift on the fault that bounds the Little Ajo Mountains on the north side and before the andesites of Black Mountain were erupted, the pediments are clearly younger than the lavas. In fact, the pediment at Darby Well is cut on the upthrown block along the Black Mountain fault, which cuts the lava at Black Mountain, but no pediment is visible on the downthrown block fronting the andesite mountain. The virtual restriction of pediments to the mountain fronts not formed of lava thus requires explanation. This may be found in the manner in which the different kinds of rock respond to weathering, the same control that determines a "younger" topography on the mountains of andesite lava flows than that on those composed of other kinds of rock, as mentioned in the description of the mountains. The thick flows of andesite yield large blocks that are not readily moved on slopes of low gradient and that do not readily break down to finer sizes. Thus,

the talus slopes of large lava blocks are stable and recede slowly, and, consequently, pediments below them can only slowly be formed. This relation between pedimentation and size of weathering debris from various kinds of rock is discussed more fully on pages 341-343.

There is a rather marked correlation between the areas of well-planed pediment and the distribution of the several geological formations in the Little Ajo Mountains and Chico Shunie Hills. The wide pediment along Darby Arroyo is cut on the Tertiary fanglomerate, the wide pediment of Copper Canyon (only a minimum extent of which is shown) on soft tuffaceous andesite, and the wide pediment north of the Chico Shunie Hills largely on a coarse, much broken and cataclastic quartz monzonite. On the other hand, pediments are not widely developed on the pre-Cambrian(?) gneiss or on the large body of quartz monzonite that makes up most of the Little Ajo Mountains. Both of these are massive and, generally speaking, relatively little fractured rocks.

There is, of course, a similar correlation between the width of the pediment within the mountain mass and the size of the stream along it, but, as the stream courses are only subordinately and locally along faults or fissure zones, the size of the streams is largely controlled by the lithology and is not, in general, an independent factor in determining the development of the pediment.

SURFACE OF THE PEDIMENTS

The pediments of the Ajo quadrangle are all more or less dissected. Toward their upper end, they are trenched by dendritic streams arranged in a finely textured pattern. The surface is, thus, a gently rolling one, in part made up of flat-topped, gravel-bearing interfluves, but in much larger part of bare rock, cut into a hill-and-valley topography (Pl. 2, fig. 2; Pl. 3, fig. 3). The depth of these valleys averages perhaps 40 feet toward the head of the pediment. Probably less than 10 per cent of the surface next the mountains is gravel-covered.

The depth of the channeling progressively diminishes toward the bahadas, and the average depth at the lowest bedrock exposures is perhaps 15 feet. In the same direction, the proportion of the surface that is flat-topped interfluve also increases, and the texture of the drainage pattern seems to become somewhat coarser (Pl. 3, fig. 2). Accordingly, there are relatively fewer gradual slopes transitional from the interfluves to the stream channels and relatively more steep arroyo walls. As the flat interfluves are more or less strewn with gravel, the proportion of the surface that is mantled by gravel also increases toward the valleys until finally there is no demarcation between pediment and the alluvium of the bahadas. The distribution of the gravel mantle, the apparently systematic variation in the side slopes of the arroyos, and the texture of the

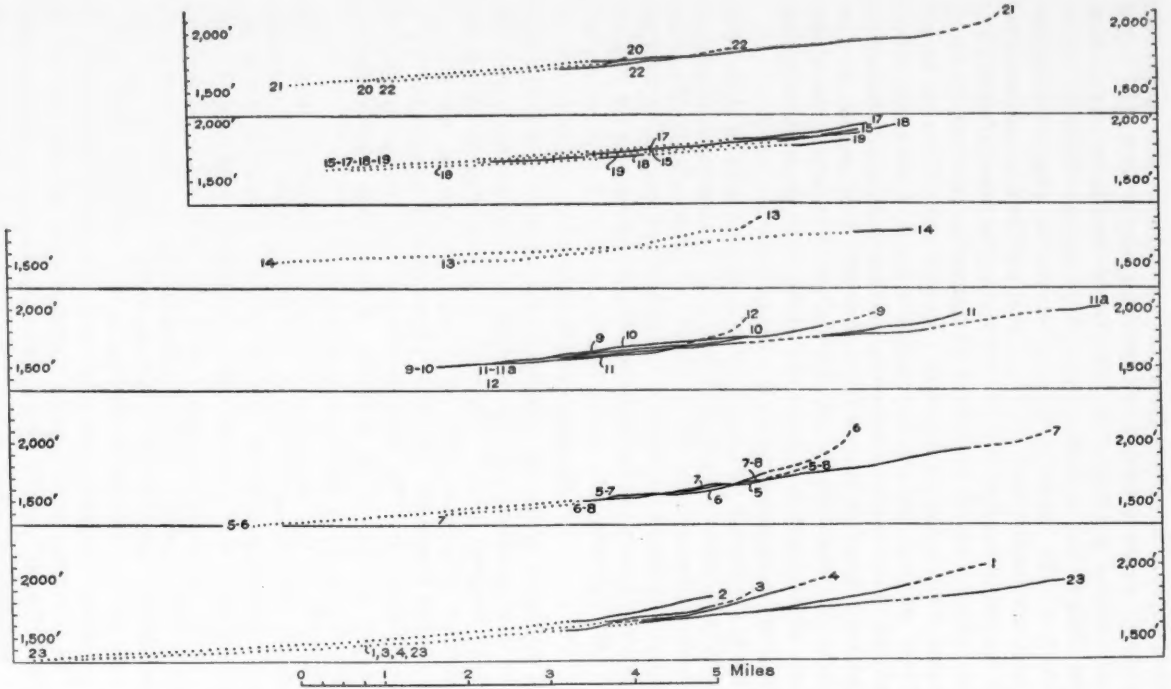

FIGURE 2.—*Profiles along streams of the Little Ajo Mountains*

Numbers refer to streams shown on Figure 3. Solid lines, pediments; dashed lines, mountain areas; dotted lines, bahada slopes.

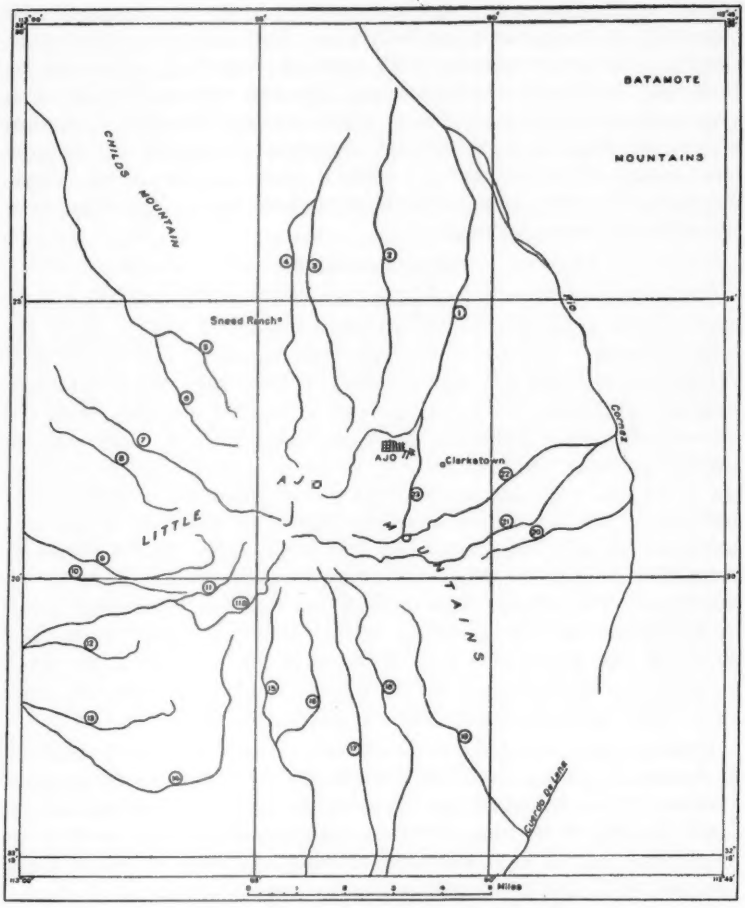

FIGURE 3.—*Streams of the Little Ajo Mountains*

Profiles are shown in Figure 2.

drainage pattern may furnish clues to the processes active in formation of the pediments.

SHAPE IN PLAN

The pediments extend for greater or less distances into the mountains along all the larger streams. They narrow headward, presumably because of less stream capacity in this direction, although the narrowing of the pediment along Darby Arroyo more or less corresponds with the wedging

out of the fanglomerate bedrock toward the west. Furthermore, the narrowing of pediments along both Chico Shunie Arroyo and Copper Canyon also closely coincides with upstream narrowing of the formations most favorable to pedimentation. Even on uniform bedrock, however, each segment of the pediment widens outward from the mountains, and, as the mass of the Little Ajo Mountains is roughly circular, the outer margin of the pediment as a whole is convex in plan. Any outward-sloping surface conforming to the mountain base must, of necessity, have this shape, whatever its origin.

SHAPE IN PROFILE

The pediment is, for the most part, concave upward in profile, generally more steeply along the smaller stream courses, less steeply along the larger streams. The gradients range from about 70 feet to the mile (about three quarters of a degree), along the lower segments of the larger streams, up to about 300 feet to the mile (about 3¼ degrees), along the upper parts of the pediments cut along small streams. The average slope is probably less than 150 feet to the mile (1⅔ degrees) fronting the north and northeast segments of the mountain mass and perhaps 100 feet to the mile (more than one degree) on the west, south, and southeast fronts. These figures fall low in the range (half a degree to 7 degrees) assigned by Blackwelder [8] to the slopes of pediments in the Southwest. The average slope is much less than the 2½ degrees, given by Blackwelder as average for the region. However, Bryan [9] states that 50 to 200 feet to the mile (half a degree to 2⅕ degrees) is the range of slopes of the pediments in the Papago country, so that the pediments near Ajo are probably fairly representative of this section.

Profiles drawn along the main streams of each of several segments of the mountain mass are shown in Figure 2; Figure 3 shows the streams. Profiles 1, 2, 3, 4, and 23 are taken on the northeast quadrant of the Little Ajo Mountains, nos. 5 to 8 on the northwest slopes, nos. 9 to 12 on the west, nos. 13 and 14 on the southwest, nos. 15 to 19 on the south, and nos. 20, 21, and 22 on the east.

It is apparent from these profiles that in each segment of the pediment—that is, for each given type of rock—the larger the stream the lower the gradient of the adjacent pediment. When gradients of pediments cut on different rock types are compared, it is clear that the lithology exercises a marked control that commonly outweighs the factor of stream size. Rocks yielding relatively coarse and resistant debris have steeper pediments than those yielding relatively finer and friable debris.

[8] Eliot Blackwelder: *op. cit.*, p. 137.
[9] Kirk Bryan: *op. cit.*, p. 95.

The size of material yielded to the headwaters of the streams also may impose a steeper gradient than would be "normal" to a given formation. Thus it happens that on tuffaceous and relatively friable rocks even small streams generally have pediments with low gradients. On the other hand, massive formations that yield large blocks on weathering do not permit the cutting of pediments with such low gradients even along the larger streams.

Whether or not the size and amount of material yielded by the massive monzonite is the determining factor, there is obviously a steeper slope for large streams like nos. 1 and 23, which drain areas made up of this rock and run northward across fanglomerate and andesite, than there is for much smaller streams like no. 15, which drains soft, friable volcanics and fanglomerate. Although part of this difference in gradient may be due to climatic factors—the northern exposures being less readily degraded than the southern—east-west valleys wholly within the mountain mass show no recognizable systematic differences that might be ascribed to this control. The climatic factor is thus regarded as not likely to explain these differences in gradient.

Two of the profiles, nos. 10 and 18, show reverse curvature—*i.e.*, change from concave upward to convex—although no. 10, west of Chico Shunie village, is nearly a straight line. No lithologic boundaries correspond to the change in curvature, and they may be due to piracy along these streams affecting the stream volumes. They are clearly not exhumed "suballuvial platforms" such as are described by Lawson[10] and Paige,[11] because the neighboring streams on each side do not show this upward convexity. The cause then is in the local history of the individual stream.

SHAPE IN CROSS-SECTION

Whether pediments are characteristically convex or concave in cross-section (rock fans) at the mouths of streams is a moot point in the study of desert topographic forms.[12] As can be seen from Plate 1, on which the pediment areas have been delimited according to the criteria outlined on page 325, the evidence is conflicting in the Little Ajo Mountains. There seems to be a definite rock fan at the mouth of Gibson Arroyo (Figs. 2 and 3, no. 1). The critical area at the mouth of Cornelia

[10] A. C. Lawson: *The epigene profiles of the desert*, Calif. Univ. Dept. Geol., Bull., vol. 9 (1915) p. 34-38.

[11] Sidney Paige: *Rock-cut surfaces in the desert ranges*, Jour. Geol., vol. 20 (1912) p. 444.

[12] D. W. Johnson: *Planes of lateral corrosion*, Science, n s., vol. 73 (1931) p. 174-177; *Rock fans of arid regions*, Am. Jour. Sci., 5th ser., vol. 23 (1932) p. 389, 416; *Rock planes of arid regions*, Geogr. Rev., vol. 22 (1932) p. 656-665.

Eliot Blackwelder: *Desert plains*, Jour. Geol., vol. 39 (1931) p. 137.

Ross Field: *Stream carved slopes and plains in desert mountains*, Am. Jour. Sci., 5th ser., vol. 29 (1935) p. 313-321.

Arroyo (no. 23) is obscured by the tailings dump, but there is no reason to suspect a convexity here. All the other pediment segments are perceptibly concave toward the streams rather than fan-shaped.

It is perhaps noteworthy that Gibson Arroyo, of all the streams of the quadrangle, drains the largest area of resistant rock. It has a large

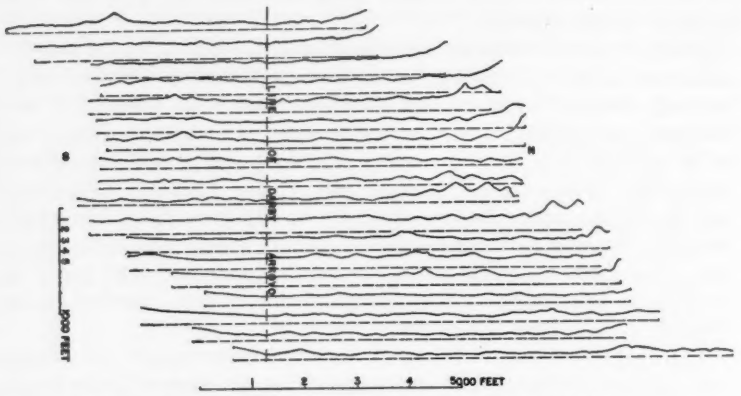

FIGURE 4.—*Cross-sections of the pediment along Darby Arroyo*

Drawn normal to the local course of Darby Arroyo, at intervals of 1,000 feet. Lowest section is through the north spur of Black Mountain; highest is near Ajo Peak. The sections are normal to a crooked stream, so their extremities are not equidistant from each other, as are the points where they cross the arroyo course.

catchment basin, almost wholly in massive, tough quartz monzonite. It thus fulfills the conditions outlined by Bryan [18] as favoring fan forms of pediments, for it carries a heavy load of resistant detritus that must tend to accumulate at the canyon mouth and from time to time deflect the stream laterally.

The pediment of Darby Arroyo is one of the best developed in the area. It is carved on the dominantly soft fanglomerate and volcanics, dipping steeply to the south. The United States Geological Survey topographic map of the Ajo mining district excellently portrays this pediment on the scale of 1 : 12,000, with contour interval of 5 feet. Sections were drawn transverse to the local course of Darby Arroyo, at intervals of 1,000 feet along it, from a point north of Black Mountain nearly to Ajo Peak. These sections are shown in order in Figure 4. It is obvious that, despite minor irregularities, each cross-section is concave upward. This pediment is within the mountain front and might not, on this account, be

[18] Kirk Bryan: *The formation of pediments*, 16th Internat. Geol. Cong., Rept., Washington, D. C. (1933); preprint (1935) p. 8.

expected to show a fan section even though such forms were dominant at the mountain front. However, it is clear that a moderate lateral growth of this pediment would reverse the relation (Pl. 1; Pl. 3, fig. 2). Instead of a pediment within the mountain mass, there would then be island mountains (Locomotive Rock and others) isolated within broad pediments. Certainly such additional widening would be slight compared to what has already been effected along Darby Arroyo, and, if it took place, a broadly concave pediment would still exist here, crowned by sierra remnants.

This concavity is an obvious necessity in areas of coalescent drainage such as characterize most of the upper parts of the pediments. As long as the stream pattern is dendritic the master stream must clearly be at an axis of lower altitude than the tributaries. The lower reaches of the pediments where the streams are parallel or divergent, such as north of the mouth of Copper Canyon and the lower pediment north of Darby Arroyo, may be slightly fan-shaped, but the best-developed pediment as far as exposed bedrock goes—that northwest of Chico Shunie Well—is concave throughout. Insofar as the pediments of the Ajo quadrangle are representative, there is clearly neither general convexity nor general concavity in cross-section where the streams leave the mountain front, but by far the greater part of the pediments are concave rather than convex.

BAHADAS

Most of the Ajo quadrangle, like the Papago country as a whole, is buried by alluvium. The broad valleys differ from the valleys of humid regions in being not primarily the work of stream erosion but of structural deformation. As the mountains show selective erosion of some rocks, probably parts of the valleys are also modified by erosion, but it is clear that the dominant result of stream action in them is deposition. Most of the low land is low because it has been relatively depressed by faults. This is shown by the entire lack of relation between the size of a drainage area and the size of the valley draining it, by the presence of a transverse divide in the middle of the broadest valley of the area—the Valley of the Ajo—and by the gravels buried to great depths in the bottom of the valleys. The hard, resistant andesite buried by 170 feet of alluvium at Childs Siding (3 miles north of the area shown in Pl. 1) could not have been cut down by erosion from a height equivalent to Batamote or Black Mountain and still leave the fanglomerate at Darby Well standing 800 feet higher, because the planed pediment at Darby Well was cut without notable modification of the bold peak of the adjacent Black Mountain.

The gently sloping alluvial fans that occupy the depressions cannot

be sharply separated from the pediments that so commonly skirt the mountains above them, because the pediments are veneered more or less completely with gravel (Pl. 2, fig. 1). At the axial depressions of the valleys the bahada fronting one mountain mass coalesces with that fronting the mountain on the opposite side, the position of the axis being determined, in the absence of tilting of the valley block, by the relative supplies of debris from the two sides.

The slopes of the bahada are moderate, ranging between 15 and 75 feet to the mile, with 50 feet to the mile as, probably, a fair average. The profiles of these slopes normal to the mountain front, like those of the pediments, are concave upward, in consequence of the basinward diminution in size of the detritus as it is transported from the mountains. Also, like the pediments, the alluvial slopes are steeper on the north than on the south side of the Little Ajo Mountains, perhaps because of the difference in the coarseness of the material supplied from the bedrock on the two flanks of the mountains.

The depth of the gravels composing the alluvial fans is uncertain but probably is very irregular. As summarized by Bryan,[14] the alluvium at no. 1 well (Childs Siding) is 173 feet deep and at Childs Well, 7 miles farther southeast, it is at least 820 feet deep, for the well apparently did not reach bedrock. So great a depth of alluvium at Childs Well is inconsistent with the idea that the bedrock there is a buried part of the pediment that borders the Little Ajo Mountains to the west. The eastward projection of the pediment along Darby Arroyo at its maximum slope would intersect Childs Well at a depth of not more than 400 feet, so that, even allowing for a suballuvial bench convex upward, as postulated by Lawson,[15] the reported depth of alluvium is much too great to allow the suballuvial bench to extend this far. This deduction must, however, be qualified, because the driller's log of the Childs Well may not have distinguished the soft Tertiary fanglomerate from the alluvium. If this be so, it is possible that part of the great thickness reported as alluvium may be Tertiary fanglomerate, and the pediment may intervene between them. Be this as it may, it is difficult to avoid the inference—from (1) the known faulted structure of the area, (2) the wide extent of the alluvial deposits in the Papago country, and (3) the fact that the drainage is almost wholly integrated—that the alluvium is not simply a veneer covering a suballuvial bench, but, that, in some places at least, it fills structural basins below the local base-level attained by the streams. Widespread shallow dissection of the deposits through-

[14] Kirk Bryan: *The Papago country, Arizona*, U. S. Geol. Surv., Water-Supply Paper 499 (1925) p. 179-180.

[15] A. C. Lawson: *op. cit.*, p. 34-38.

out the Papago country [16] and the continuous drainage lines show that the fans are not essentially below grade and that the detritus now being brought onto the bahadas by the mountain streams is approximately in balance with the material removed by the exterior drainage; hence, that the present bahada slopes are determined by transportation rather than by deposition of material.

The material composing the alluvial deposits has a considerable range in size. Near the mountains, pebbles up to approximately 3 inches in diameter make up much of the alluvium, and cobbles up to a foot in diameter are common. The grade size of the material diminishes rapidly, and, a mile or so from the mountains, pebbles as large as 4 inches in diameter are rare and tend to be in nests and local patches. Silt and sand dominate beyond 2 miles from the mountains. The only exceptions to this rule noted were south of Cameron Arroyo, where lava boulders 2 feet or more in diameter incompletely mantle the alluvial slopes on the east flank of the Growlers for several miles from the mountains. They are much larger than those carried by the present streams, which are incised in the bahada, and the boulders are probably let down by erosion from an older, higher gravel or conglomerate. Locally, probably because of deflation of smaller particles, there is a desert-pavement of gravel formed on the bahadas (Pl. 3, fig. 1).

DRAINAGE

The drainage of the Little Ajo Mountains is radial (Fig. 3). All the drainage lines extend to the Gila River, some, such as the Rio Cornez and Copper Canyon drainages, fairly directly, others, such as Cameron Arroyo and the Cuerdo de Lena, by circuitous routes. The course of the drainage from the Cuerdo de Lena to the Gila is tortuous, and nearly twice as long as that from the Rio Cornez. Probably none of these drainage lines is ever occupied throughout by flowing water; they are maintained by local storms, and water rarely flows for more than a few hours at any one locality.

Although radial in general pattern, the streams are notable for their remarkable parallelism for distances of several miles, especially on the pediments. Even here, they are dendritic on the upper slopes, but lower on the pediments the branches of the several main drains extend parallel for some distance. This is especially notable west and northwest of Darby Well, but it may be seen at many other places. In detail, the stream channels on the pediments are anastomosing; locally, they meander. The bahadas are carved by many channels that commonly branch and reunite, both high on the slopes and along the valley axes.

[16] Kirk Bryan: *op. cit.*, p. 107.

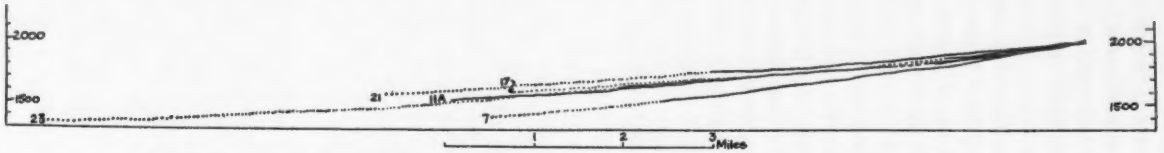

FIGURE 5.—*Longitudinal profiles of streams whose pediments are practically confluent near Ajo Peak*

Showing differences in gradient. Dotted lines are on alluvial fill, solid lines on pediment surfaces.

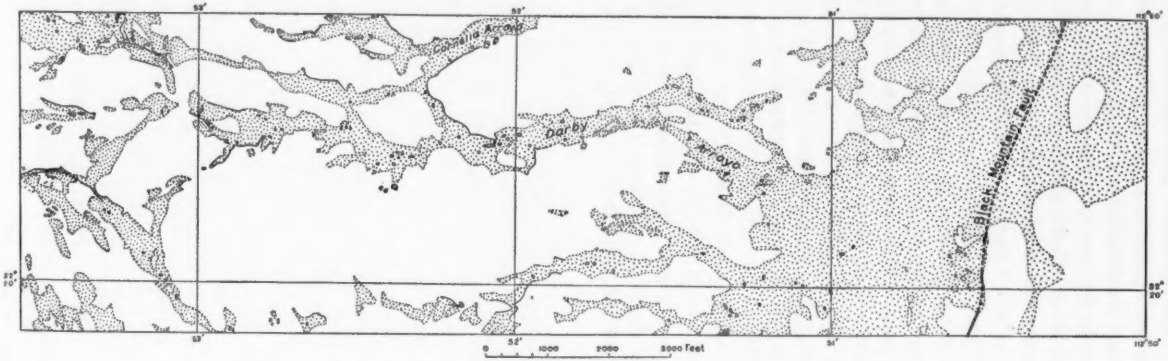

FIGURE 6.—*Distribution of alluvium along Darby Arroyo*

For the most part, the streams are incised into both pediments and bahadas. In the bahadas the trenching is generally slight—depths of 2 to 4 feet are common along the axial streams—and similar channeling is widespread on the lower slopes. Some of the channels, though, are as much as 6 or 8 feet deep, even on the lower slopes. Practically all the stream trenches that are continuous from the mountains deepen upstream. Many channels, however, grow shallow headward and die out on the bahadas within relatively short distances. At the lower end of the demonstrable pediments the streams have commonly cut to depths of 10 feet. Locally, this dissection was brought about in two stages, with a terrace several hundred feet wide forming in the interval. The terraces are cut on alluvium and disappear headward where they meet the pediment. Toward the upper limits of the pediments, some of the larger streams are sunk as much as 40 feet (Pl. 2, fig. 2; Pl. 3, fig. 3). Rarely, if ever, are these deep trenches fully occupied by water; they are valleys, not channels, and are clearly younger than the smooth gravel-coated parts of the pediment into which they are sunk. The shallower trenches of the lower alluvial slopes, however, may often be filled to overflowing, so that an anastomosing pattern is developed.

The drainage of the west slope of the Little Ajo Mountains is notable in that from a point about 2 miles south of Salt Well to a point 3 miles southwest of Chico Shunie Well, the alluvium and pediments are scored by shallow channels trending northwesterly, but the major, deeper trenches uniformly trend more westerly or southwesterly. Whether this indicates a southwesterly tilt of the mountains here, a downdropping along the south side of Daniels Arroyo (no. 14) of a block that probably extends northwestward beyond the map area, or some other cause, is uncertain. Downfaulting of the valley block seems more likely than tilting of the mountain block, because the straight boundary of alluvium against the wall of Daniels Arroyo would probably have been embayed if the mountain block had been tilted.

A circle a mile in diameter, with its center half a mile east of North Ajo Peak, encloses pediment areas tributary to six different radial streams (Fig. 3; Pl. 2, fig. 2; Pl. 3, fig. 3). Clockwise from the north, these are Cornelia Arroyo (no. 23), Darby Arroyo (no. 21), an unnamed south-flowing stream (no. 17), a similar more westerly stream (no. 15), Chico Shunie Arroyo (no. 11a), and Copper Canyon (no. 7). Figure 5 shows the longitudinal profiles of these streams (except no. 15, which is like no. 17), superposed at about 1,980 feet, where their pediments are practically confluent. From this drawing it is evident that all the streams have essentially the same gradients except Darby Arroyo (no. 21), which is much gentler than the average, and Copper Canyon (no. 7), which is

much steeper. As all these streams appear to be graded throughout, the only apparent explanation of these differences in grade lies in the differences in their drainage areas and in the bedrock over which they flow. Copper Canyon is cutting siliceous gneiss; Darby Arroyo, the poorly consolidated Tertiary fanglomerate. The greater drainage area of Darby Arroyo is probably explained by the fact that it is cutting softer rock than Copper Canyon, and its greater drainage area tends to increase the discrepancy in gradient. This seems to be an example of the development of headwater basins with low passes, such as are described by Bryan[17] and Waibel.[18]

The asymmetry in the slopes on the north and on the south of the Little Ajo Mountains is obvious from the topographic map (Pl. 1). The streams seem to be slightly more deeply incised into the pediments on the north than they are on the south of the mountain mass, but the differences between adjacent streams in the depth of these incisions on both sides is great enough to throw doubt on the reality of a systematic difference in the depth of dissection on the two sides. If it exists it may reflect a tilting of the mountain block, but the channel cutting does not differ greatly above and below the trace of the Little Ajo fault, so that any earth movement recorded in these different slopes was not localized along this fault.

ORIGIN OF THE PEDIMENTS

The processes recognized as active in the formation of pediments include lateral corrasion of streams, rill wash, and the weathering of slopes with removal of debris by rills.[19] Doubtless other factors, such as sheet floods,[20] are also involved, but recent students of these surfaces have principally concerned themselves with the relative efficacy of the processes enumerated.[21]

[17] *Op. cit.*, p. 88-90.

[18] Leo Waibel: *Gebirgsbau und Oberflächengestalt der Karrasgebirge in Südwestafrika*, Mitt. deutschen Schutzgeb., Bd. 33 (1925) p. 82-83; *Die Inselberglandschaft von Arizona und Sonora*, Zeitschr. Gesell. Erdk. Berlin, Jubilaums Sonderband (1928) p. 89.

[19] Kirk Bryan: *op. cit.*, p. 96.

[20] W J McGee: *Sheetflood erosion*, Geol. Soc. Am., Bull., vol. 8 (1897) p. 87-112.

[21] Sidney Paige: *Rock-cut surfaces in the desert ranges*, Jour. Geol., vol. 20 (1912) p. 442-450.

A. C. Lawson: *The epigene profiles of the desert*, Calif. Univ. Dept. Geol., Bull., vol. 9 (1915) p. 23-48.

Kirk Bryan: *op. cit.*

Leo Waibel: *op. cit.*

W. M. Davis: *Rock floors in arid and humid climates*, Jour. Geol., vol. 38 (1930) p. 1-27, 136-158; *Granite domes of the Mojave Desert, California*, San Diego Soc. Nat. Hist., Tr., vol. 7 (1933) p. 211-258.

Eliot Blackwelder: *Desert plains*, Jour. Geol., vol. 39 (1931) p. 133-140.

D. W. Johnson: *Planes of lateral corrasion*, Science, n. s., vol. 73 (1931) p. 174-177; *Rock planes of arid regions*, Geogr. Rev., vol. 22 (1932) p. 656-665; *Rock fans of arid regions*, Am. Jour. Sci., 5th ser., vol. 23 (1932) p. 389-416.

Siegfried Passarge: *Das Problem der Inselberglandschaften*, Zeitschr. Geomorph., Bd. 4 (1929) p. 109-122.

Paige was inclined to emphasize the work of lateral planation of streams in the production of pediments, an idea that had been developed by Gilbert as long ago as 1877.[22] This is also the view of Johnson, who declared that certain deductive reasoning, not detailed in the papers cited, required that, if pediments be primarily the work of lateral planation, they should characteristically be fan-shaped rather than trough-shaped, and that, in fact, the absence of a fan shape would be a strong argument against origin by stream planation. Blackwelder and Field, though advocates of lateral planation by streams as the major process in pedimentation, do not find the pediments to be fan-shaped, as a general rule; they apparently regard concavity as no argument against origin by planation. Lawson evidently considered rill wash as the dominant process in pedimentation but is not explicit in the matter. Bryan, though emphasizing the effects of unconcentrated rill wash, recognized lateral planation as especially effective at and below the mouths of the major canyons. His observation was, however, that the pediments have lower angles opposite larger streams than opposite smaller ones and that they are still steeper in the interstream areas,[23] thus being generally concave upward rather than fan-shaped. He regarded the common lack of meanders in the streams as showing that lateral planation does not dominate in forming the pediments. This is evidently Davis' view, also. Rich regards unconcentrated rills as the principal factor in pedimentation; he reasons that pediments should be fan-shaped even on this theory[24] —the exact antithesis, apparently, of Johnson's conclusion.

As summarized on page 335 and shown in Plate 1, the pediments of the Little Ajo Mountains are chiefly trough-shaped, but one is definitely, and two are perhaps, fan-shaped. For the most part, their upper sections are concave, as is required by their possessing dendritic drainage; their middle sections, with braided streams, are probably nearly flat, transverse to the stream courses.

Whatever the factors involved in the production of the pediments, it seems worth while to emphasize that here, at least, they are not developed on the massive basaltic andesite flows of Black Mountain, Childs

Hans Mortensen: *Der Formenschatz der Nordchilenischen Wüste*, Abhandl. Ges. Wiss. Göttingen, Math.-Phys. Kl. N. F., Bd. 12 (1927) p. 1-191; *Inselberglandschaften in Nordchile*, Zeitschr. Geomorph., Bd. 4 (1929) p. 123-138.

Ross Field: *Stream carved slopes and plains in desert mountains*, Am. Jour. Sci., 5th ser., vol. 29 (1935) p. 313-321.

J. L. Rich: *Origin and evolution of rock fans and pediments*, Geol. Soc. Am., Bull., vol. 46 (1935) p. 999-1024. Rich uses the term "sheet wash" in a way that appears to make it synonymous with "rill-wash" as used by Bryan.

[22] G. K. Gilbert: *Report on the geology of the Henry Mountains [Utah]*, U. S. Geog. Geol. Surv. Rocky Mtn. Reg. (1877) p. 126-133.

[23] Kirk Bryan: *op. cit.*, p. 96.

[24] J. L. Rich: *op. cit.*, p. 1011.

Mountain, and Batamote Mountain. The development of pediments is apparently conditioned by the lithology of the terrane, the softer and more readily disintegrated rocks forming more extensive pediments than do the harder and more resistant rocks. Although the flows at Black Mountain are clearly older than the pediment of Darby Arroyo (p. 329) there are no pediments cut on them. Their physiographic development is generally youthful; the pedimented mountains, on the other hand, are invariably maturely dissected. The pediment development is probably conditioned by the same factors that control this difference in stage of the physiographic cycle in the adjacent mountains. The only apparent factor that might explain this contrast in physiographic stage is the size of the fragments yielded by weathering of the rock masses. Bryan, agreeing with Lawson, has pointed out the correlation between the average size of rock spalls and the average declivity of the mountain slopes. This factor may also control the slope, and hence the degree of perfection of the pediments. Lawson has recognized that granitic rocks, which disintegrate to individual grains, [25] furnish flatter slopes than other hard rocks in the desert. Obviously, this slope angle is a measure of the relative rapidity with which physiographic evolution proceeds on the several parts of a heterogeneous terrane, and as pediments represent mature or later stages in the arid cycle, they are commonly better developed on granitic rocks and soft sediments than on other rocks.

In his careful descriptions of 79 mountain masses in and near the Papago country, more than 45 of which contain Tertiary volcanics (many of which must include massive lava flows), Bryan mentions no pediments carved on this sort of rock. Wherever the pediments are well enough developed to be worthy of comment, they are reported as cut on "gneiss," "granite," "Tertiary sediments," or on heterogeneous volcanics.

Callaghan[26] states that, in the Searchlight district, Nevada, massive lava flows are the only rocks that project significantly above the pediment that is there developed on granitic and brecciated volcanic rocks. Moore [27] reports similar observations in the region of Tucson.

The cross-sections of the pediment transverse to Darby Arroyo reveal a consistent shallow trough shape. This, of course, is what would be expected inside the mountain mass, but, as the further development of this pediment must lead to isolation of several groups of hills from the main mountain mass, so that they will eventually be left as "islands" on the pediment, it seems fair to conclude that well-graded pediments can be trough-shaped for long distances, and even that this is their usual form. As there is only one (perhaps two) of the more than twenty radial

[25] A. C. Lawson: *op. cit.*, p. 45.
[26] Eugene Callaghan: *oral communication.*
[27] B. N. Moore: *oral communication.*

streams of the Little Ajo mass that shows a fan-formed segment of the mountain pediment, it seems likely that fan forms also are not characteristic of frontal pediments. To whatever extent this fact is inconsistent with the dominance of lateral planation in pedimentation, as Johnson asserts, doubt is thereby thrown on the necessity of that process.

Along Copper Canyon, a narrow pediment coalesces headward with the pediment drained by Darby Arroyo (Pl. 1). At an earlier stage in the erosion history, the pediments were wider (Pl. 2, Fig. 2). Bryan[28] illustrates the head of the Darby pediment. These wide coalescing pediments are now also found southwest of Darby Well and along Chico Shunie Arroyo. The divides have, of course, migrated somewhat, but they are not deeply notched. These features do not support the theory that lateral planation is the controlling process in pedimentation; it is difficult to see how streams could migrate widely at the divides.

The local relief of the pediments increases notably headward. This means, of course, that the surface defined by the interfluve summits—the "dissected" pediment—is still more markedly concave than is the surface defined by the stream channels of today. The present streams are flowing on lower gradients than that marked by the surface of the interfluves; if the pediment were molded by stream meandering, one might reasonably expect the present streams to be widening their valleys by meandering. Generally, the streams on the pediments meander only locally. Commonly, the channels are braided. This, of course, does not bear any necessary relation to the stream habit at the time that the pediment was being formed, and the present habit may not be the one they had when the "interfluve" surface was made. Nevertheless, the rounding of the divides between secondary, tertiary, and smaller tributary streams, the fine texture of the drainage toward the heads of the pediments and the coarser texture downstream, the patchy distribution of gravel, and the common exposures of bedrock on the interfluves, all permit a doubt as to the necessity of postulating a former meandering habit of the streams. In the same measure, there is doubt that the pediment surface was smoothed chiefly by the lateral corrasion of the streams.

In fact, the obvious effectiveness of tributary streams and rill wash in lowering the surface at present arouses a tentative question: Is it necessary to postulate a change in climatic cycle to account for the "dissection" of the pediments? If, as seems clear, the interstream areas, at least near the heads of the pediments, are today being lowered chiefly by tributary streams and rill wash, may one not suspect that the pediments were, so to speak, "born dissected"? If, as appears from the literature,

[28] Kirk Bryan: *The Papago country, Arizona,* U. S. Geol. Surv., Water-Supply Paper 499 (1925) pl. 10a.

no undissected pediments are definitely known, is it simply because they are concealed beneath a veneer of gravel? One may grant that it is difficult to mark a boundary at the junction of pediment and bahada and also that the streams in this boundary region meander somewhat (or even widely). Nevertheless, if the present topography gives a clue to the formerly planed surfaces, gravels were by no means continuous on them prior to their dissection. The area along Darby Arroyo has been mapped on a scale of 1:12,000 and the gravel is patchy on the even interfluves themselves (Fig. 6 and the geological map of the Ajo mining district to be published by the United States Geological Survey). Is it necessary, then, to conclude that pediments are smoothed and traversed laterally by freely wandering streams?

If they be so traversed, one might reasonably expect the "planes of lateral corrasion" to narrow, possibly notably, where hard rocks were encountered. One would, however, expect at least rudimentary planation even of massive rocks. Instead, not exceptionally, but almost universally, blocky lavas are not even notched by the pediment surface, although adjacent granitic and clastic rocks have been lowered hundreds or thousands of feet. The relations are such as might be expected if the streams were primarily agents of transport rather than of abrasion, and, indeed, suggest that lateral planation, which prevails just above the bahada boundary, does little more than smooth the few remaining irregularities on a surface already far advanced toward a plain. Surely, this is the suggestion from the relations along Darby Arroyo, and, though the fan-shaped pediment of Gibson Arroyo may record greater lateral planation at an earlier stage in pedimentation (i. e., higher up the slopes), the Gibson Arroyo fan is unique in the quadrangle. In other regions the relations may, of course, be reversed, but for this district the evidences of the effectiveness of rill wash and weathering in pedimentation are more impressive than are those of lateral planation.

Bryan has, however, concluded, largely from studies in New Mexico and eastern Arizona,[29] that lateral planation is relatively more effective during youth and maturity; rill wash and weathering, during old age. This rather startling conclusion does not seem to be borne out by the relations at Ajo, at least if one regards pedimentation in a local area as the old-age stage. If a larger area is considered, so that the existence of mature mountains at the head of the pediment is sufficient to characterize the physiographic stage as mature, it might be accepted, but it does not appear to be positively supported by the facts known to the writer.

The question of "congenital" dissection of the pediments must be

[29] Kirk Bryan: *The formation of pediments*, 16th Internat. Geol. Cong., Rept., Washington, D. C. (1933); preprint (1935) p. 10.

qualified, at least in part. The topographic contrast between interfluves and arroyo walls at the lower ends of the pediments is too great to represent an equilibrium condition. There probably has been, as Bryan suggested, a change in the stream regimen since these parts of the surfaces were formed. However, the topographic contrasts become less and less upstream, and the upper portions of the pediment, though still rather sharply divisible from the mountains, are occupied by slopes transitional from the interfluves to the tributary streams. Palo verde trees, which grow in some of the stream channels high on the pediments north of the Little Ajo Mountains, range up to 3 inches or more in diameter. The annual accretions of the palo verde are visible only with a hand lens.[30] These trees must be scores, if not hundreds, of years old and show the "dissection" of the upper pediment to be old in years. There is no evidence to date the sharp dissection farther downstream, but it seems far younger. Possibly, the upper parts of the pediment were cut in much the present form while the lower parts were still smooth surfaces.

Whatever the cause of the "dissection" of the pediments in the Ajo quadrangle, it cannot be referred to lowering of local base-level. The channel of Rio Cornez has been sunk little, if any, below the constructional surface at the pass between Batamote and Childs Mountains, and the channels in the bahadas are, in general, shallow, although the pediments at their heads may be dissected to depths of 40 feet or more. The tributaries of the Cuerdo de Lena show similar incision into the pediments but practically fade, as definite streamways, before joining the shallow master channel. These features are general in the Papago country and have been interpreted by Bryan[31] as results of an increase in the available water in the streams, in proportion to the available sediment, and not due to change in base-level. The lowering of base-level, as evidenced by terraces along the Gila, San Pedro, and other large, nearly perennial streams of southern Arizona, has not taken place in the Ajo region. Bryan's conclusion, that the widespread dissection of pediments implies a climatic change from a somewhat drier to a somewhat wetter period, seems reasonable, at least insofar as it refers to the lower part of the pediments. As he mentions, this does not necessarily imply that the present is a wet period, but simply that the last climatic change effective in altering the stream regimen was in the direction of greater humidity. However, one may doubt that all the dissection is due to this change. Much of it may have continued with the planation of lower parts of the pediments. The degradation of arid regions, like that of humid regions, need not lead to a completely smoothed surface, even in old age.

[30] Forrest Shreve: *Establishment behavior of the palo verde*, Plant World, vol. 14 (1911) p. 292.

[31] Kirk Bryan: *Erosion and sedimentation in the Papago country, Arizona*, U. S. Geol. Surv., Bull. 730 (1922) p. 63-65.

Surfaces far advanced in the erosion cycle may still proceed further in their evolution by general slope wash, rill transportation, and resulting continual regrading of the surface.

Baker[32] has pointed out that, after maturity has been reached, there is a continual decrease in supply of material to the streams, so that they should normally cut down their channels without any necessity for a climatic change. Possibly, this is the true explanation of the dissection in this region, because, as has been pointed out, the pediments are confined to the fronts of sierra type (mature) mountains.

The abrupt change in declivity of the surface at the junction of mountain slope and pediment has been stated by Field to be inconsistent with the hypothesis that rill wash is a dominant process in pedimentation.[33] However, if, as suggested by Davis,[34] in accordance with Lawson and Bryan, the pediment gradient is conditioned by the minimum slopes on which the detritus can be transported and the mountain slopes by the angle of repose of blocks acted on by gravity almost entirely, there seems no necessity for the two slopes to merge more than they actually do. Davis has pointed out[35] that this contrast in angle of bedrock slopes exists in humid regions, also, and is there masked by soil creep, a factor that is less effective, or absent, in arid regions. The absence of pediments at the foot of massive lava mountains and the commonly gentler transition from mountain slope to bahada that they exhibit seem to accord with this concept. The widespread existence of basin-shaped pediments on granitic rocks that break down to individual grains is a strong argument for the efficacy of rills in molding the pediments.

The efficacy of rills and slope wash in the arid regions is much greater, on the average, than in humid regions, for, although the weathering in humid regions commonly yields finer-grained detritus than does weathering in arid regions, the vegetation cover hampers the rill-work relatively much more. This doubtless outweighs the factors of grain-size and available water, for most erosion surfaces in arid regions are further advanced than are erosion surfaces of comparable geologic age in humid regions.

Nothing seen by the writer in the Ajo quadrangle appears inconsistent with the conclusions of Bryan—that pediments are slopes of transportation peculiar to arid regions and formed by cooperation of lateral cor-

[32] C. L. Baker: *Notes on the later Cenozoic history of the Mohave Desert region in southeastern California*, Univ. Calif. Dept. Geol., Bull., vol. 6 (1911) p. 376-377.

[33] Ross Field: *Stream carved slopes and plains in desert mountains*, Am. Jour. Sci., 5th ser., vol. 29 (1935) p. 317, 321.

[34] W. M. Davis: *Rock floors in arid and in humid climates*, Jour. Geol., vol. 38, no. 2 (1930) p. 136-158.

[35] *Op. cit.*, p. 149.

rasion, rill wash, and weathering, with subsequent removal of detritus by rills. One process may dominate in one place and another elsewhere, but all are operative.

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DEVELOPMENT AND PRESENT STATUS OF GEOLOGY IN NORTH AMERICA

BY W. C. MENDENHALL

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EARLY EUROPEAN INFLUENCES

In Europe at the end of the eighteenth century and the beginning of the nineteenth century, geology began to emerge definitely from the shadows of speculation as a science in something approaching the modern sense. If any one man among the number who contributed to this emergence were to be denominated as its founder, historians of the science would doubtless agree that that honor belongs more clearly to the Scot, James Hutton, than to any other.

His contemporary, Werner, at Freiberg, was much more influential at the time, but it is Hutton's work rather than Werner's that history has approved. Werner, trained in law and in mineralogy, drawing pupils from the entire civilized world of that period and, in the words of Geikie, so teaching mineralogy that it "embraced the whole of nature, the whole of human history, the whole interests and pursuits and tendencies of mankind," influenced, through his pupils, the geologic thought of the world for two generations, but in many respects influenced it wrongly and thereby delayed the acceptance of the far sounder Huttonian principles and methods.

Playfair's classic interpretation of Hutton's *Theory of the earth* appeared in 1802, five years after Hutton's death. The soundness of Hutton's observations, his strict adherence to the inductive method, his objectivity and convincing logic, as set forth by Playfair, introduced order and method into a philosophy, which before his time had been largely fragmentary and chaotic, a compound of a minimum of observation and a maximum of fantastic deduction.

Hutton's clear separation of sedimentary and igneous rocks; his irrefutable proof that granites are intrusive and that in the process of in-

trusion they have brought about changes in the rocks into which they were intruded; his recognition of an orderly succession of events in the deposition of the sediments; and his convincing advocacy of the idea that the processes of weathering, transportation, and deposition now observable everywhere are processes that fully account for the succession of stratified rocks—all this is so modern, both as to method and as to conclusions, that in reading Hutton one feels that he is reading a contemporary.

No one man who spoke or wrote with equal soundness or who left so deep an impress on the science followed Hutton until the appearance of Charles Lyell, who was born in 1797, the year of Hutton's death. This statement, I believe, may be made without disparagement of the great contributions by William Smith, who introduced geologic mapping in Great Britain with his "Geologic atlas of England and Wales", issued in 1815, or of the work of Sedgwick and Murchison, who in the 1830's, applying to the older rocks of Great Britain the paleontologic and stratigraphic methods established earlier by Brongniart and Cuvier in the Paris Basin, distinguished and named the Devonian, Silurian, and Cambrian systems.

Lyell, a man of independent means, wide travel, and broad culture, an indefatigable collector of material, and a lucid writer, published the first edition of his *Principles* in 1830. His method, like Hutton's, was chiefly inductive. He greatly expanded Hutton's thesis that the earlier history of the earth and of the rocks in which that history is recorded is fully explained by processes now under way and observable. Darwin's great generalizations appeared long before the end of Lyell's period of activity and were adopted and supported in Lyell's geologic philosophy. As he conceived it, not only life on earth but the earth's own physical history was a process of orderly evolution.

Hutton, the sound observer and, as interpreted by Playfair, the impeccable logician, and Lyell, the great expositor, are then perhaps the two men to whom, among many, most credit is due for the emergence of a clearly defined and comprehensive science of geology, from the vague cosmogonies, the crude mineralogies, and the beginnings of paleontology, which preceded them.

EARLY WORK IN AMERICA

On this continent at the beginning of the nineteenth century the science had few adherents and received little attention, but both interest and contributions grew rapidly during the first three decades of that century, while the adherents of the Wernerian and Huttonian schools were contending in Europe.

This early period is discussed in detail by Merrill under the captions "The Maclurean era" and "The Eatonian era". It is of interest to us

here and now chiefly as a period in which we can discern the very definite beginnings of interest and accomplishment in matters geologic in the New World, inspired both by the literature from England and the continent and by the appearance in 1809 of Maclure's *Observations on the geology of the United States*, with a colored geologic map of the area east of the Mississippi; of Parker Cleaveland's textbook in 1816; and of Eaton's *Index to the geology of the Northern States*" in 1818 and his *Geological textbook* in 1830. Maclure's own chief contribution, his *Observations on the geology of the United States*, is easily the most significant of the earlier part of the period and justifies Merrill's designation of the time as the Maclurean era and of Maclure himself as the William Smith of America.

Amos Eaton may perhaps be called the first professional geologist, in that he was employed by Stephen Van Rensselaer in 1821 to make a geological and agricultural survey of Rensselaer County, New York. He was forceful, emphatic, and active, traveled and lectured widely, had no aversion to controversy, and did much to stimulate interest in the emerging science. But the influence of Werner, displayed in an overemphasis on catastrophism and plutonism, mars many of Eaton's writings, which show particularly the tendency, so gratifyingly absent in Hutton, to speculate far beyond the inferences justified by his observations.

Before the end of the first third of the century, enough had been done on this side of the Atlantic to inspire in the minds of a few men a definite consciousness of a most alluring new field of thought and a vast new continent to which to apply it. Prior to this period, geology as a comprehensive science had not been taught anywhere, unless the magnetic Werner may be said to have taught it at Freiberg.

Hutton was a farmer and a chemist, with a degree in medicine. His Boswell, Playfair, taught mathematics at Edinburgh. William Smith was a yeoman and surveyor. Maclure was a Scotch merchant. Amos Eaton was trained as a lawyer. Even Benjamin Silliman, appointed in 1802 to the professorship of chemistry and natural science at Yale, was, prior to this appointment, a tutor in law who had but recently been admitted to the bar. Writing of educational conditions in London in 1805, Silliman says, "I found there no school, public or private, for geological instruction and no association for cultivation of the subject, which was not even named in the English universities."

Not only, then, was geology recognized by very few as a separate department of natural science in the early years of the last century, but it was not then formally taught, and the workers of that time were entering upon a complex and little-known field without such training as might even then have been given by a few men in the world, had the educational institutions been able to utilize them. Under these conditions the progress

made both in direct accomplishment and in interest during the first three decades of the century is truly astonishing.

Among the factors in this progress had been the establishment of the American Journal of Science in 1818 and of the American Geological Society in 1819, and Schoolcraft's explorations in the Mississippi Valley in 1818-1821. Moreover, the growing industries of the young country were utilizing more and more of its mineral products, particularly the coal and iron of the Eastern States. All these elements together were creating a background and a state of mind that finally led to the establishment of the earlier series of State surveys, in the decade from 1830 to 1840. No less than 15 such surveys were launched during this time. While they all suffered serious vicissitudes and many were short-lived, others continued after interruptions, and the place of the science in the economy of the United States was beginning to be recognized.

Massachusetts, Tennessee, Virginia, New York, Ohio, Pennsylvania, Indiana, and New Hampshire were among the States that initiated official surveys during the decade. The elder Hitchcock, Troost, the Rogers brothers, and James Hall, to mention only a few of the more famous men associated with these organizations, began studies which led to official reports that profoundly affected both the basic concepts and the economic status of geology as the new continent began to yield its contributions.

In 1839, J. D. Dana, pupil of Silliman, author at the age of 24 of the *System of mineralogy*, destined to become one of the great creators and teachers of our science, began his work with the Wilkes Expedition. In 1834, G. W. Featherstonehaugh was authorized by the War Department to undertake a geological and mineralogical survey of the Ozarks, and at the end of the decade, David Dale Owen conducted his remarkable exploration of the lead and zinc lands of Iowa, Wisconsin, and northern Illinois for the General Land Office. Thus, the Government itself was beginning vaguely to recognize and to use the profession.

During the succeeding decade, several of the State surveys were abandoned. Science was too slow for State legislatures, or its products were economically too intangible to secure support from nonscientific administrators. Some of the geologists were not practical men; the times were hard, and the wave of interest and activity receded. It had probably risen too rapidly: the young science could not always deliver as much in the form of practical results nor deliver them as quickly as laymen expected. But, meanwhile, some of the better-organized, better-financed, and better-conducted surveys were issuing reports that commanded popular as well as scientific attention. Instruction in geology was increasing and improving; the literature of the science was steadily growing; and in the decade before the Civil War there was a strong revival of State activity. New States were admitted to the Union, and several, California among them,

created geological organizations. Six of the States that had abandoned such organizations re-established them. The Federal Government attached geologists to several of its Pacific railroad surveys in the Far West. Lesley's *Manual of coal* and Whitney's *Metallic wealth of the United States* were published. James Hall's volumes on the paleontology of New York were beginning to appear, and Albany was becoming the mecca, not only of American but also of European geologists. The Geological Survey of Canada had been launched in 1842, with Sir William Logan as its first director. Agassiz had joined the Harvard staff in 1847, adding immediate prestige to the small American group, and through his success as a teacher and a lecturer he contributed much to interest in science generally and in geology in particular. Sir Charles Lyell had made four visits to this continent, in 1841, 1846, 1852, and 1853. His *Travels* and his *Second visit to the United States* had augmented the growing interest here and in western Europe, fostered by what John M. Clarke calls "the volcanic outburst of reports from the geological surveys throughout the States from 1835 to 1845." The science on this continent was definitely breaking away from the leading-strings of Europe. A new panorama was unfolding; the extraordinary New York section of the Paleozoic was being revealed, its extinct life elucidated and interpreted, and its units defined with an approach to precision. The Rogers brothers, H. D. and W. B., had set forth, with striking clearness and accuracy for the time, the Appalachian type of structure. Agassiz's glacial hypothesis was gaining ground and stimulating thought, even though it was to be long before this hypothesis found complete acceptance and, of course, still longer before all the marvelous details of the various ice advances that have been revealed to us by the modern glacialists became known.

Inevitably, the Civil War so completely absorbed the energies and the thoughts of the Nation, both in the North and in the South, that the period of its duration was one of relative inaction in geologic matters. In the South, where the war's effects were most severe, all geologic work ceased, some of the records were lost, and resumption in later years was slow. In the North the eclipse was less complete, but, nevertheless, it was a period of little progress, although before it was over Dana's *Manual* and *Textbook* had both been issued.

Considering the Civil War period as the end of an era, we may briefly recapitulate the progress made in geology during that era. At the beginning of the century, geology was a very immature science indeed. It was taking form in Europe, and there we can discern the germs of some of the present concepts. Cuvier and Brongniart had demonstrated the value of fossils in geologic chronology and had "established the principles of paleontological stratigraphy."

Hutton had effectively undermined the Wernerian doctrine that granites

and trap rocks are aqueous precipitates, had recognized their intrusive nature and their metamorphic effects, and had established the inductive method as applied to rocks and their relations, although his ideas were not to prevail until long after their announcement.

William Smith had shown the possibilities and the value of areal mapping in England, and Maclure had prepared the first crude map on this continent. Eaton, Silliman, Dana, Agassiz, and Sir William Dawson had introduced systematic geologic instruction in American schools. Canada and most of our States had established official surveys, some of them directed by remarkable men who made permanent contributions both to the available body of geologic fact and to the principles of the science. Journals and societies had been established, and several textbooks had appeared. The Association of American Geologists had been organized at Philadelphia in 1840. Out of it had grown in 1847 the American Association for the Advancement of Science, from which came eventually this Society. The literature, including many official reports, had greatly expanded. Darwin's provocative and stimulating *Origin of species* appeared near the end of the period. Several editions of Lyell's lucid and widely read *Principles* had been published. The Government had attached geologists to some of its exploring expeditions and had used them in determining the mineral values of public land.

Our science was well established by 1860. It had emerged from the nebulous, indefinite, and confused beginnings of the first years of the century. It was fully recognized as a separate science, as a culture, and as a highly practical activity.

POST-CIVIL WAR PERIOD

After the war, some of the State surveys that had survived it were strengthened, others were re-established or newly established, and work of high value was resumed. Professor Hall, through many battles and many vicissitudes, continued his work in New York, and his aid was invoked in building State organizations in the Mississippi Valley and in the Lake region. The public demand in Pennsylvania, arising out of the rapid development of its mineral resources, led to the creation there of the Second Survey under J. P. Lesley, who had obtained his training under H. D. Rogers. Merrill pays this deserved tribute to the Second Geological Survey of Pennsylvania: "From the work of this organization has sprung up the most remarkable series of reports ever issued by any survey."

First under Newberry and later under Orton, the Ohio State Survey functioned effectively. Its roster lists a brilliant galaxy of men who were later to be recognized as among the leaders of their generation—Meek, Cope, Marsh, Whitfield, Stevenson, N. H. Winchell, and G. K. Gilbert. Joseph LeConte in 1869 joined the faculty of the University of California,

there to begin the distinguished career as a stimulating teacher that continued until his death in 1902. Shaler and Proctor made the Kentucky Survey famous, and Shaler at Harvard became one of the most successful teachers and creators of geologists. Dana's career and influence at Yale continued. T. C. Chamberlin was placed at the head of the Wisconsin Survey, and N. H. Winchell of the Minnesota organization. Eugene A. Smith in 1873 became the head of a revived Alabama Survey, where he was to continue for more than half a century, a beloved teacher and an influential leader of geology in the South.

But so far as official surveys are concerned, perhaps the most important development that followed the Civil War was the increased participation of the Federal Government in geologic work. The end of the war released abundant energies and turned the attention of the Nation to the great areas beyond the Missouri, largely public land, undeveloped and to a great extent unknown. The Pacific railroad surveys, conducted before the war, had revealed some of the geography and geology of the routes traversed, and the excursions of Evans and of Hayden and Meek into the valley of the Missouri had made known the existence of rich paleontologic material that stimulated the desire for further work.

The four great National post-war surveys of the West were conducted under various auspices. Hayden's Geological Surveys of the Territories were made under the General Land Office; King's Geological Survey of the Fortieth Parallel was under War Department auspices but civilian direction and control; Wheeler's Geographical Surveys west of the One Hundredth Meridian, under Army auspices and military control; the United States Geological and Geographical Survey of the Rocky Mountain Region, by J. W. Powell, privately initiated, then under the administration of the Smithsonian Institution, and after 1874 under the Interior Department. These surveys opened the West geologically and geographically, greatly enriched our literature, revealed vast new problems, and, because of the spectacular conditions under which they were conducted, attracted much public attention. As they expanded, however, they began to overlap, and rivalries developed. Congress took the matter in hand, extended hearings were held, the advantages of military versus civilian control of engineering and scientific work and of public versus private support of exploration and research were debated, and finally in June 1878, the problem was referred to the National Academy of Sciences, which was asked "to take into consideration the methods and expense of conducting all surveys of a scientific character * * * and to report to Congress * * * a plan for surveying and mapping the Territories of the United States on such general system as will in their judgment secure the best results at the least possible cost * * * ."

The Academy reported in the following November, setting up a succinct

plan, which, however, was adopted only in part by Congress. The members of the Academy committee who signed the report were O. C. Marsh, J. D. Dana, W. B. Rogers, J. S. Newberry, W. P. Trowbridge, Simon Newcomb, and Alexander Agassiz. It would be difficult to conceive of a more competent group to pass upon such a question, remembering, of course, that the leaders of the existing surveys were of necessity omitted from the committee.

The final action of Congress on the problem took the form of the act of March 3, 1879, discontinuing the separate national surveys and establishing as their successor the present United States Geological Survey, with Clarence King as its first director. Most of the scientific leaders of the preceding surveys were appointed to its staff, so that we find on its roster during the first year of its existence the names of such geologists as F. V. Hayden, Raphael Pumpelly, C. E. Dutton, G. K. Gilbert, S. F. Emmons, Arnold Hague, George F. Becker, Charles D. Walcott, and J. P. Iddings. Interestingly enough, the name of Major J. W. Powell, who perhaps had been the most effective of the leaders of that day in urging the creation of the new organization and who within two years was to become its second director, does not appear on the roster.

Thus, the Federal Government, after many desultory excursions into the geological field, was finally systematically launched upon this work. Theretofore a geologist often had been merely a sort of tolerated camp follower attached to an expedition whose main object had been exploration or topographic reconnaissance. Gilbert sets forth this situation very clearly in a prefatory note to a limited edition of his Wheeler Survey papers issued in 1876. He says:

> "The observations that form the basis of these reports were hurried in the extreme. The writer, for the most part, accompanied field parties which were especially equipped for rapidity of movement and were crowded to the utmost. Moreover, in a country almost unmapped, the demand for geographical information was more urgent than that for geological, and all plans and routes were accordingly and with propriety shaped to give the topographer the best opportunities consistent with rapidity of movement, while the geologist gleaned what he could by the way. To study the structure of a region under such circumstances was to read a book while its pages were turned quickly by another, and the result was a larger collection of impressions than of facts."

The work done by the Hayden, Powell, and King Surveys, however, was not controlled by these exigencies; hence, Clarence King regards 1867, the year when the King Surveys and the later systematic surveys of the Hayden organization were authorized, as the beginning of a new era in national participation. He says "Eighteen hundred and sixty-seven, therefore, marks, in the history of national geological work, a turning point, when the science ceased to be dragged in the dust of rapid exploration and took a commanding position in the professional work of the country."

In the Congressional debates leading up to the establishment of the Federal Survey, Representative James A. Garfield expressed a point of view, neither new then nor extinct now, but one whose continued expression and discussion will serve to keep before us the question of a healthy balance between national and individual or institutional activities. I quote from a speech delivered by Garfield in the House of Representatives on February 11, 1879:

"What ought to be the relation of the National Government to science? What, if anything, ought we to do in the way of promoting science? * * * Generally the desire of our scientific men is to be let alone to work in free competition with all the scientific men of the world; to develop their own results, and get the credit for them, each for himself; not to have the Government enter the lists as the rival of private enterprise.

"As a general principle, therefore, the United States ought not to interfere in matters of science, but should leave its development to the free, voluntary action of our third estate, the people themselves."

Perhaps I am justified in departing from the chronologic order at this point to present a contrasting view enunciated much later, also by a statesman, but one who is in addition a man of scientific training. I quote from an address by Herbert Hoover, then Secretary of Commerce, before the American Association for the Advancement of Science at Philadelphia on December 28, 1926:

"How are we to secure the much wider and more liberal support to pure-science research? It appears to me that we must seek it in three directions—first, from Government, both National and State; second, from industry; and third, from an enlargement of private benevolence. We have long since accepted the obligation upon the State to provide universal and free education. We have advanced it further than any nation in the world. Yet the obvious function of education is to organize and transmit our stock of knowledge; it is not primarily concerned with the extension of the borders of knowledge except so far as the process is educational. It seems to me that we must accept the fact that the enlargement of our stock is no less an obligation to the State than its transmission."

PRESENT STATUS

By the close of the period that ended about half a century ago, our science had become firmly established as one of the well-nigh indispensable activities in western civilization. It was recognized by the educational institutions as one of the richest of the cultures. None surpassed it in stimulating a broadening of interest in the things about us. None offered a greater reward for one whose faculties for observation and interpretation were adequately trained. None required greater capacity for both exact observation and creative and controlled imagination. None gave a more penetrating perspective on life, its origin, its development, and its meanings, or on man's place in that nature of which he is a part. And with this

recognition of its cultural value there has been a steadily rising tide of recognition of its practical value.

The educational institutions have responded fully to this dual challenge. It is long since a student who desired instruction in our science has been limited in his choice to one or two institutions. There are successors to Dana and Shaler, LeConte and Dawson, and Van Hise and Chamberlin in thirty or more great institutions of learning on this continent. Well-rounded geologic departments exist in many of these schools, with full staffs giving instruction in the various branches of the science. Members of these staffs are themselves leaders in research and offer full opportunity to the ambitious student, both for the cultural and for the applied aspects of geology, and the field that opens after graduation is constantly broadening. That field is no longer limited, as it once was, to teaching or to a few places on the official surveys.

Industry, during this century particularly, has learned the wisdom of using the geologist's special training. Although this movement was well under way at the outbreak of the World War, it received a special impetus during that crisis. Executives and specialists were assembled in Washington from all parts of this country for service in the common cause. The associations, there established, broadened acquaintanceship and built up mutual respect. Business learned not only that scientists in many fields, geology among them, had highly valuable types of specialized information, but that they usually possessed special capacities also. As a result, after the war, many of these men were offered opportunities in the commercial field, and the educational and scientific institutions suffered many losses in personnel. This, however, meant an infiltration of trained scientists into business and corporate counsels. Each man thus placed was a center of influence for his profession and its ideals. His tendency was to surround himself with other men of similar training and to promote the establishment of research units and research methods in industrial organizations.

Although, as we all know, American industry lagged far behind European industry in recognizing the value of research, it has made much progress in this respect during the present century. So far as our own science is concerned, many of us can remember the time when it was rare to find a geologist on the staff of a mining or an oil company. It is now almost equally unusual to find a well-managed company without a corps of geologists, and not rarely they are highly placed in the management itself. Similarly, there has been a rapidly awakening consciousness of the necessity for geologic counsel in many of the more general problems of government, of economics, and of engineering. Instances of costly failure adequately to consider the effect, on local and national policies, of the distribution of minerals and their place in the field of economics have been recognized. Disasters to engineering structures through failure to fore-

see some geologic weakness in the site or plan have brought home to engineers the necessity for geologic advice, and that advice is being sought more and more.

All these factors are broadening the field for geologic graduates. Educational institutions are continually adapting their instruction to the recognized needs, and their students by the hundreds are finding opportunities that were not open to the graduates of the last century.

As the universities have thus met their growing responsibilities in our fields, so also have governments. Half or three quarters of a century ago, our science had won recognition and acceptance. The intervening period has largely been one of development and use. States, provinces, and governments have, as a rule, expanded their geologic activities. There have been temporary setbacks, for advance is never uniform, but, on the whole, it has been continuous. Canada has maintained an official Survey of expanding usefulness since 1842; the United States since 1879. Nearly all our States have related organizations—some of them, to be sure, poorly supported, but others well financed and highly efficient.

Meanwhile, associations devoted to geology have expanded in number and in membership, and publications have multiplied. Trained geologists have increased in numbers from a few tens a century ago to a few hundreds half a century ago to several thousands now.

The science itself has, of course, obeyed that law of evolution in the establishment of which it has supplied such essential evidence. It early developed species and varieties. It has constantly become more highly specialized, until it has become a group of sciences rather than a single science. Moreover, it recognizes not only the necessity of specialization if advance is to be maintained but also the parallel necessity of supplying correctives for this tendency, in the form of group attack on major problems. Staff work, the cooperation of several specialists on a single problem, is now common practice in research and in application.

Now what does this accepted status of geology mean in everyday terms, and what is ahead of us?

We must constantly remember that we are living in an age in which the scientific method has largely won its battle for recognition. In fact, its victory is, in some respects, embarrassingly complete. It sometimes seems as if the world were depending upon science for the solution of all its problems—social, political, economic, or other. The social organism appears at times to sit back helplessly and complainingly and say to science, "we expect you to solve all our problems for us, whether they are within your field or not." It complains both that science has done too much—has made man too efficient—and that science has done too little—has not shown society how to control its great efficiency. Naïvely

it asks impossible things, and it asks that possible things be accomplished in an impossibly short time.

Success, of course, breeds imitation. As a consequence, all sorts of weird activities are now labeled "scientific" by their promoters. These activities have the same relation to science that burglary has to honest business. But the world in general naturally is unable to discriminate between the false and the true in unfamiliar fields. It is prone to accept gaudy self-applied labels. And, not discriminating between the genuine and the spurious, it complains that science has led it astray.

Geology, of course, participates with all the other sciences in these experiences. I mention them only to illustrate the place that science now occupies in the world, because such experiences do not come to a movement that is struggling for recognition, but only to one that is widely accepted. A label is not worth imitating unless it has value. So, although in a physical sense geology has far more work to do than it has yet done, in the sense of acceptance of its relation to life, to society, and to the problems of civilization its pioneering days are over. We are accepted and adopted, and we are expected to play our part. We are a fully credited member of the great family of sciences and of human activities. It is long since we have been strangers in either the intellectual or the practical field. It is our task to continue in the van of both, and thus to continue to make our contributions to man's advance as a thinking being and in his intelligent adaptation to and use of natural forces and materials.

Even so, perhaps it is less exciting to be a geologist in 1936 than it was in 1800 or in 1850 or 1875. The philosophic battles between the Neptunists and the Plutonists are over as truly as are the Napoleonic wars. But were they really any more thrilling than the present discussion over the age of the earth? We no longer debate as to whether fossil shells found far inland on a mountain side or a plateau top were left there by the Noachian deluge or whether indeed they are organic at all, although remnants of these queries may even yet be encountered in our remoter countrysides. But surely, the discussion as to whether the submerged Hudson River channel is erosional or tectonic is scarcely less interesting. A geologist no longer risks his standing among educated men or subjects himself to possible banishment—other perhaps than from an occasional local school—if he ventures to suggest that the earth may be more than 4,000 years old. Except in isolated areas, he no longer finds his profession on the defensive and endangering its respectability if it supports, as Lyell did, the doctrine of evolution. But he may be subjecting himself to scarcely inferior hazards if he ventures to tell an enthusiastic community that its hopes for developing a particular mining industry are without foundation.

It is sometimes said that the great discoveries in geology have been

made, that all the great geologists belong to history, that research is no longer active, and that our science is now a prosaic, practical, matter-of-fact profession. Let us briefly consider some of these points of view.

Columbus discovered America. That was a dramatic event. It cannot be repeated, but the four and a half centuries of further discovery, of occupation and settlement, and of reduction of the continent to use that have followed, while possibly less dramatic than the discovery itself, are no less important to mankind.

Geology was discovered long ago. It is now engaged in the cultivation of its field and in the development and application of its principles. But even in this process, it has participated in many dramatic events in man's intellectual progress. It will participate in many more. To be sure, how many or of what nature cannot be foreseen. But it is safe to say that what is now known about the earth and its development, about the origins and evolution of life, including man himself, and about earth processes is infinitesimal by comparison with what will eventually be known.

Someone recently quoted to me a statement made by a great physicist only a little more than a generation ago. He said in effect: "All the laws and all the great principles of physics are known." Yet in a few years that statement had been completely nullified by the developments in our sister science.

Similar statements about geology are certain to be as far from the truth. It seems to be a common weakness of mankind that each generation tends to believe that it is seeing the culmination of progress and that the future is to be relatively static. Why do most of us lack the imagination to realize that things and principles, of which we have not yet dreamed, nevertheless exist? We have too little faith in the capacity of our successors to discover that which we ourselves have not yet discovered.

Not only are there more men in our profession in this generation than in any earlier one, but they are far better equipped than their predecessors. They are capable of and are doing just as clear thinking, and they have a vastly greater and a constantly growing body of well-determined fact to which to apply their thinking processes. The contributions that they are making to the advancement of our science are quite as sound and as permanent, in my personal opinion, as those past contributions that we often refer to with awe as the products of the masters.

And undeniably, we are constantly becoming more useful. To borrow a phrase from George Otis Smith, "geology is at work" in a practical sense. This fact is sometimes mentioned apologetically and is often coupled with an expression of concern over an alleged decay of research. Official organizations particularly are accused of this neglect. Even educational

institutions have been accused of devoting themselves to education (!) instead of to research or of permitting or even encouraging faculty members to apply their special knowledge practically in the service of mankind through industry.

It is true, of course, that tax-supported organizations must make a return in direct usefulness for the grants of public funds that support them. Not only does this necessity require no apology; any other attitude would unquestionably require one.

But I do not believe that these organizations neglect research. The principles of efficiency and the instinct of self-preservation alone require that they maintain it. It is an axiom among them that there can be no applied science unless there is science to apply, and the best of them attempt, I believe with success, to keep a proper balance between research and its application, for they realize that research is the life blood of applied science.

A scrutiny of the records will reveal large contributions to research and to the establishment of geological principles by the publicly supported organizations on our continent. A few such contributions may be mentioned in passing. The names of the Rogers brothers are forever associated with the problems of Appalachian structure. Professor Hall and Paleozoic paleontology are almost synonyms. Lesquereux, Stevenson, Ward, Fontaine, White, and Knowlton established paleobotany on this continent. Many volumes on vertebrate and invertebrate paleontologic research are to be found among official reports, as well as among the products of the university groups. Physiography was largely established as a branch of geologic science by Powell, Gilbert, Dutton, and their associates from the official surveys, and by Davis and others from the university groups. Secondary enrichment is associated particularly with the names of Weed and Emmons; the carbon-ratio hypothesis is the product of David White's studies. Glacial research owed its advances to both official and educational leaders, but more largely perhaps to the educational. Isostasy on this continent is linked with the names of Dutton, Gilbert, Hayford, and White. The developments in petrography and mineralogy and the constitution of rocks have been shared, with the educational institutions making the larger contributions. Geologic mapping, with all that it develops as to critical relations, naturally falls rather in the field of the public surveys than in that of studies under other auspices. The present illuminating work on the age of the rocks of the earth's crust is being shared among individuals, endowed institutions, and educational and official groups.

Perhaps it is not necessary to say more in answer to the criticism, occasionally heard, that the public surveys neglect those phases of our science that do not have immediate economic value.

I grant that the tax-supported geologic institutions are less free in this pursuit than are the endowed. They conduct much valuable research, but little of it can be called the pursuit of science solely for science's sake. The normal and proper objective of their research is to acquire facts or establish principles to apply in ways that are useful to the social organism. Pure research, undefiled by thought of application, is the appropriate field for the great foundations and, to a lesser degree, for the universities.

In its Geophysical Laboratory, the Carnegie Institution of Washington, one of these foundations, is now occupying a special portion of the geologic field and is throwing an illuminating light on obscure relations. Elsewhere, it is supporting highly specialized geologic studies, unhampered by limitations of time or by legislative doubts.

But this Society is now, thanks to Dr. Penrose's munificence, *the* great geologic foundation. It is in a position to foster any desirable project in geology anywhere on this continent. It has no responsibility to an impatient public for practical results. It has no obligations other than to geologic science itself. But because of its very freedom, its responsibilities are serious. It must see that the available funds are used wisely and without waste—that they really contribute to the increase of human knowledge and human understanding in the field of geology. It must maintain flexibility and the open mind. It must not become mechanized; it must avoid the substitution of habit for thought; and it must avoid over-organization. With a few obvious precautions of this type, it should in the future round out our science by directing and stimulating pure research in otherwise neglected fields, thus maintaining a balanced advance along all fronts. Its existence should remove any lingering anxiety that may have been felt over the danger of neglect of research in our science.

In summary, it seems to me that geology in developing to its present full stature has come to fill that desirable dual rôle, of a rich culture and a very practical science. Cultivated for its own sake, it is one of the finest of disciplines, which opens to its disciples vast concepts of time and process, and eons of pre-human history leading back toward remote and fascinating beginnings of things on earth. Practically applied, it is one of the most useful of the sciences, because the materials with which it deals include a large proportion of those things derived from the earth, out of which our civilizations are builded. Mankind in a century or more has obtained glimpses of its value in both fields, but who can doubt that, measured by what the future has in store, they will prove to have been glimpses only.

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HISTORY OF THE CANADIAN RIVER OF OKLAHOMA AS INDICATED BY GERTY SAND

BY T. A. HENDRICKS

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CHARACTER AND DISTRIBUTION OF GERTY SAND

The Gerty sand consists of unconsolidated deposits, as much as 50 feet thick, of sand, gravel, and clay. The sand and gravel are almost entirely siliceous, the main constituents being quartz, quartzite, chert, flint, jasper, and silicified wood. H. D. Miser has found one pebble of schist. The silicified wood has been examined by C. B. Read, of the United States Geological Survey, who believes much or all of it to be of Cretaceous age. The nearest source for these materials is in the Cretaceous and older rocks of the Rocky Mountains or the Tertiary deposits of the high plains, which contain pebbles and cobbles derived from rocks that are exposed in and near the Rocky Mountains. A single elephant tusk, found in the Gerty sand by A. E. Brainerd,[1] suggests that the deposits are of Pleistocene age.

These unconsolidated deposits form the surface of a highly dissected and discontinuous eastward-sloping plain, about 90 miles long and locally as much as 4 miles wide. The plain extends from Byars, Oklahoma, to a point north of Haileyville, Oklahoma (Fig. 2). Several small areas of sand, just north of the Canadian River in the Muskogee-Porum district, Oklahoma, lie about at the level of the Gerty and have been correlated by C. W. Wilson, Jr.,[2] with the Gerty. The Gerty sand also

[1] G. D. Morgan: *Geology of the Stonewall quadrangle*, Okla. Bur. Geol., Bull. 2 (1924) p. 144-145.
[2] C. W. Wilson, Jr.: *Geology of the Muskogee-Porum district, Oklahoma*, manuscript in preparation.

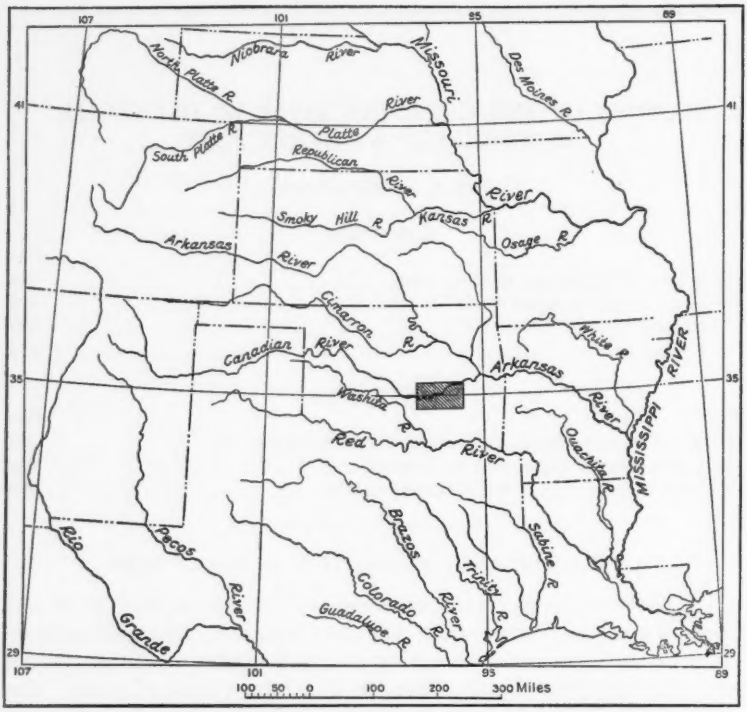


FIGURE 1.—*Map of eastward drainage from the Rocky Mountains*

has been mapped over a small area in the southern part of the Quinton-Scipio district,[3] which lies immediately north of the McAlester district.

This narrow eastward-sloping plain appears to have been formed by a large stream that flowed eastward from the high plains or from the Rocky Mountains. The Canadian River (Fig. 1) is sufficiently large to have deposited the sand, and its headwaters cross the high plains and reach to the Rocky Mountains. As the present Canadian River flows between deposits of Gerty sand in the western part of the area under consideration (Fig. 2) and flows north of the areas of Gerty farther east, it is inferred that the Canadian River deposited the Gerty sand and has since been diverted northward from the eastern part of the area where the Gerty is found.

In late Tertiary time, prior to the deposition of the Gerty sand, the

[3] C. H. Dane, H. E. Rothrock, and J. S. Williams: *Geology and fuel resources of the Quinton-Scipio district, Pittsburg, Haskell, and Latimer counties, Oklahoma,* manuscript in preparation.

Canadian River probably flowed eastward in the lower part of its course, across a widespread nearly level plain that stood about at the level of the present tops of the highest hills of the region. The Canadian River at that time was not cutting downward but was migrating laterally and forming a wide alluvial plain. The leveling of the region by stream erosion had proceeded so far that differences in the hardness of the various underlying beds of rock had little effect on the course of the stream, which cut across hard and soft beds without any apparent relation to the structure.

Later, probably in Pleistocene time, the Canadian River started cutting downward through its alluvium and into the folded shales and sandstones of Pennsylvanian age. This downward cutting of the stream may have been due to any one of several causes: there may have been tilting upward toward the west, producing higher gradient and greater erosive power for the stream; the entire area between the mouth of the Canadian River and the Rocky Mountains may have risen as a block, resulting in downward cutting that started at the mouth of the Canadian River and progressed headward; the climate may have become more humid, increasing the volume of water carried by the stream and consequently increasing the erosive power of the stream. Whatever the cause for this increased erosive power, this down-cutting continued in the lower portion of the course of the Canadian River until the river was flowing about 200 feet below the former level; but at that level the stream became graded or was even slowly depositing material. The stream migrated laterally and built up a wide flood plain underlain by gravel, sand, and clay, which constitute the Gerty sand.

There is considerable evidence that the Canadian River flowed about at the level of the Gerty sand for a rather long period. Several remnants of stream terraces, which lie about at the same level as the Gerty sand, are found in the valley of Brushy Creek, which joined the former course of the Canadian River near Haileyville (Fig. 3). As the level of this tributary was controlled by that of the Canadian River, it is apparent that the Canadian stood about at the level of the Gerty sand long enough for Brushy Creek to cut distinct terraces. The Poteau River and its tributaries, east of the McAlester district, built wide terraces at about the same level as the Gerty sand. As both the Poteau and the Canadian rivers were, and are, tributary to the Arkansas River, these terraces must have been cut while the Canadian stood at the level of the Gerty sand. Extensive terraces are present along the course of the Arkansas River in eastern Oklahoma and western Arkansas, below the mouth of the Canadian River. Those terraces now stand about the same height above

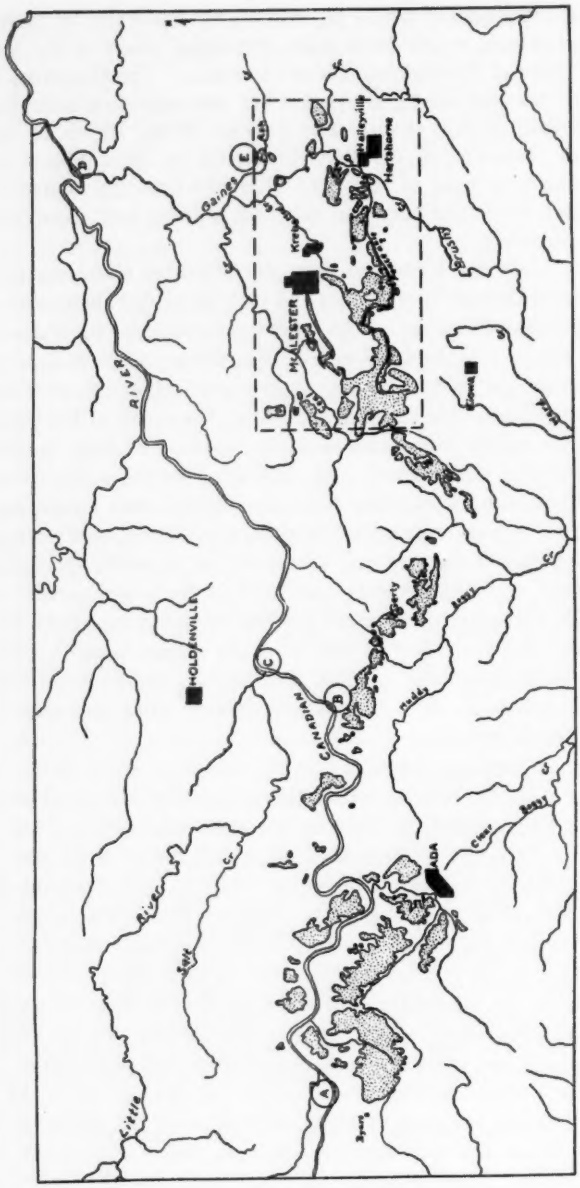
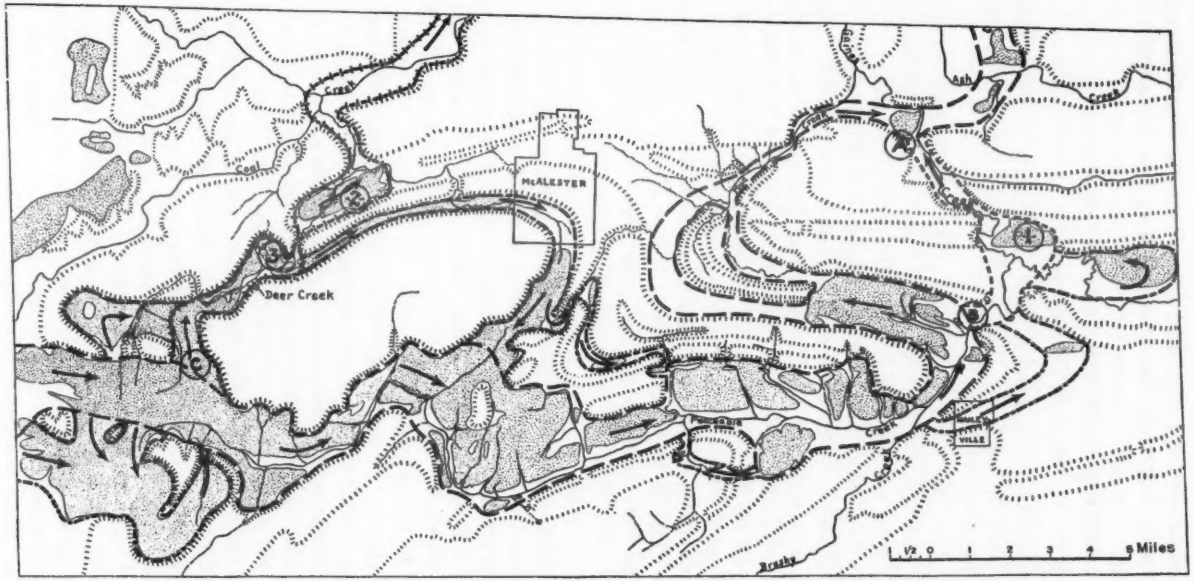


FIGURE 2.—*Known areas of Gerty sand in Oklahoma*



Boundary of original channel of Canadian River.
Boundary of first diversion of Canadian River.
Boundary of second diversion of Canadian River.
Boundary of flood channels of Canadian River.
Areas of Gerty sand.

Areas now higher than level of Gerty sand.
Direction of flow of waters of Canadian River.
1 2 3 Areas of Gerty sand outside of the original channel that contain gravel.
A B C Points referred to in text.

FIGURE 3.—*Areas of Gerty sand in the McAlester district*

the Arkansas River as the Gerty sand does above the Canadian, and probably both were formed in the same period of lateral planation by the streams.

DIVERSIONS OF THE CANADIAN RIVER

CHANNEL IN GERTY TIME

Study of the distribution and elevation of the deposits of gravel, sand, and clay that make up the Gerty sand reveals something of the history of the stream during Gerty time.

Gravel is confined to the original channel of the Canadian and to three areas (areas 1, 2, and 3, Fig. 3) not directly connected with the original channel. Only sand and clay are found in the remaining areas.

It is probable that gravel could have been transported only in the central part of the river channel, where the carrying power was greatest. Sand and clay particles could have been carried in all portions of the channel and also could have been carried by branches of the stream that occupied separate channels during times of flood. It is the writer's opinion that the areas of sand and clay that contain no gravel and are partially or entirely separated from the main channel were deposited by flood waters that overflowed the banks of the river and continued as smaller independent channels that returned to the river a few miles downstream (Fig. 3).

The presence of gravel in three deposits of sand (deposits 1, 2, and 3, Fig. 3) not directly within the original channel indicates that the course of the main stream was shifted several times in the life of the stream, so that it successively occupied channels over each of the gravel-bearing deposits. The elevations of the various gravel-bearing deposits suggest the following sequence of events, which began in Pleistocene (?) time and continued to the present.

Deposit 1 (Fig. 3), north of Haileyville, contains gravel. The top of the sand in that deposit has an altitude of less than 700 feet; the altitudes of gravel-bearing deposits in the original channel west of point B (Fig. 3) are about 755 feet. Probably the original course of the Canadian River at the time of deposition of the Gerty sand was down Peaceable and Brushy creeks to point B (Fig. 3), where it turned westward to the valley of Mud Creek, down Mud Creek to Gaines Creek, and thence across the present course of Gaines and Ash creeks to the north side of the area. A tributary of Gaines Creek, which then joined the Canadian River at point A (Fig. 3), probably started cutting headward toward point B (Fig. 3). As the distance from point B to point A was about twice as great by way of the Mud Creek valley as by this tributary and Gaines Creek, the tributary probably had a higher gradient than the Canadian River, then flowing in Mud Creek valley, and therefore cut

downward and headward while the Canadian River maintained essentially the same level. At length, the tributary cut into the channel of the Canadian River at point B, and the waters of the river were diverted into the shorter and steeper course of the tributary and Gaines Creek. The increased gradient of the Canadian River in its new course from the east side of deposit 1 to point A increased the erosive power and the transporting power of the river, and caused headward erosion, which continued from point A until the gradient was so lowered that no further deepening of the channel took place. The stream then began migrating laterally and forming new deposits of sand, gravel, and clay at a lower level than those in the former course of the river. Thus, the Gerty sand is now found at the altitude of 755 feet in the original channel and at the altitude of less than 700 feet in the Brushy Creek valley, a short distance to the east.

A second area in which gravel is present outside the original channel of Canadian River is deposit 2 (Fig. 3), which lies west of McAlester in the Deer Creek valley, at an altitude of about 600 feet. Some parts of the original channel, about 5 miles to the south, stand at altitudes of as much as 822 feet, but in the central part of the original channel the altitude of the sand is only about 720 feet. The discussion in the following paragraphs explains the apparent discrepancy between the last two of these elevations.

After the diversion of the Canadian River near Haileyville, the river flowed from the west side of the area to Haileyville, where it turned northward and pursued a relatively straight course to the north side of the area. North of the McAlester district the course of the stream must have followed rather closely the present course of Gaines Creek, as any other course would have crossed a divide higher than the level of the Gerty sand at the north side of the McAlester district.

Coal Creek, which joins Gaines Creek from the west a few miles north of the McAlester district, was at that time a tributary to the Canadian River. The distance from point C (Fig. 3) to the junction of Coal Creek with the Canadian River was about 15 miles shorter by way of Deer Creek and Coal Creek than by way of the course of the Canadian River through Haileyville. Thus, Coal Creek had a higher gradient, cut headward, and lowered its channel, as did also its tributary, Deer Creek. Finally, Deer Creek cut headward into the Canadian River channel at point C. Because of the higher gradient of Deer and Coal creeks, the Canadian River abandoned its old course and flowed in the shorter course to the junction of Coal and Gaines creeks. This shortening of the course and steepening of the gradient caused the Canadian to flow more rapidly and to erode its channel. The erosion continued until the gradient was

so reduced that deposition and erosion balanced one another. The stream then migrated laterally, building up a thick deposit of sand, gravel, and clay that stood at a still lower altitude than the sand that had been deposited prior to this second diversion of the river. Therefore, deposit 2 was formed at an altitude of only about 660 feet, and contemporaneous deposits about 6 miles upstream were formed at an altitude of about 720 feet, in close proximity with other deposits of the previous stage standing as much as 100 feet higher.

PRESENT COURSE

After the diversion of the Canadian River into the Coal Creek channel, the Little River (Fig. 2), then a tributary of the Canadian River, which it met at point D, flowed in the present course of the Canadian from C to D. The distance from B to D is about 20 miles shorter by way of C and the valley then occupied by the Little River than it is by way of the Gerty sand deposits and the Coal Creek channel then occupied by the Canadian River. Consequently, the Little River at point C soon cut lower than the Canadian at point B. A tributary to the Little River worked headward along a belt of soft shale (Wewoka formation) from C to B and diverted the Canadian River into the channel to the Little River, in the same way that the Canadian had been diverted on a smaller scale by Coal Creek and the tributary to Gaines Creek. With its higher gradient, the Canadian River cut downward in its present course until it is now about 150 feet below the level of the top of the Gerty sand at point B. The Canadian River has now cut its channel down and so adjusted itself to the present gradient that erosion and deposition are essentially balanced. It now flows on deposits of recent alluvium in a valley of normal width but in an abnormally wide flat channel, which probably is due to the fact that the river carries a heavy load of fine sediment at all times.

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PETROLOGY OF THE ALKALINE ROCKS AT RED HILL, NEW HAMPSHIRE

BY ALONZO QUINN

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INTRODUCTION

Red Hill, New Hampshire, received attention from early geologists who worked in this region,[1] and it was the subject of an extensive paper by Pirsson and Washington.[2] Although certain of the rock types were adequately described in these papers, it is apparent from field examination that the distribution of the rocks has not been shown in sufficient detail and that several of the rock types have never been described. The present paper, therefore, includes a more detailed map than has heretofore been presented, descriptions of the previously undescribed rocks, and some discussion of the relationships of the different types of rocks.

ACKNOWLEDGMENTS

The six new rock analyses here presented were made possible by a grant from the Penrose Bequest of the Geological Society of America. The writer wishes to express his sincere thanks to the Society for its generosity. He also wishes to thank Professor Esper S. Larsen and Dr. Marland Billings, of Harvard University, for valuable help in examining some of the specimens from Red Hill and in giving useful suggestions. Dr. Billings spent considerable time making comparisons with other rocks of the White Mountain magma series, which he knows so well, and he made helpful criticisms of the manuscript. Mr. C. H. Paige, of the Harvard University engineering camp on Squam Lake, lent useful maps and extended many courtesies during the field work. The idea for field determination of sodalite with red purple ultra filter was suggested by Mr. R. C. Vance of Ward's Natural Science Establishment. In field use, where large specimens or faces of rock might be studied, it was found more practical to mount the filter in a dark cloth than to use a box like the "Viewscope."

LOCATIONS AND TOPOGRAPHY

Red Hill is mainly in the town of Moultonboro, in the central part of New Hampshire. It lies between Squam Lake and Lake Winnipesaukee and is on the Mt. Chocorua and Winnipesaukee topographic sheets. The nearest village is Center Harbor. The hill rises to an elevation of 2029 feet above sea level and stands from 1300 to 1400 feet above the surrounding lowlands. The main summit, which is a little

[1] O. P. Hubbard: *Observations made during an excursion to the White Mountains in July 1837*, Am. Jour. Sci., vol. 34 (1838) p. 105-124.
C. H. Hitchcock: *Geology of New Hampshire*, pt. 2 (1877) p. 606; pt. 3 (1878) p. 132.
G. W. Hawes: *Geology of New Hampshire*, pt. 4 (1878) p. 206.
W. S. Bayley: *Eleolite-syenite of Litchfield, Maine, and Hawes' hornblende syenite from Red Hill, New Hampshire*, Geol. Soc. Am., Bull., vol. 3 (1892) p. 231-252.

[2] L. V. Pirsson and H. S. Washington: *Contributions to the geology of New Hampshire; No. III, On Red Hill, Moultonboro*, Am. Jour. Sci., 4th ser., vol. 23 (1907) p. 257-276, 433-447.

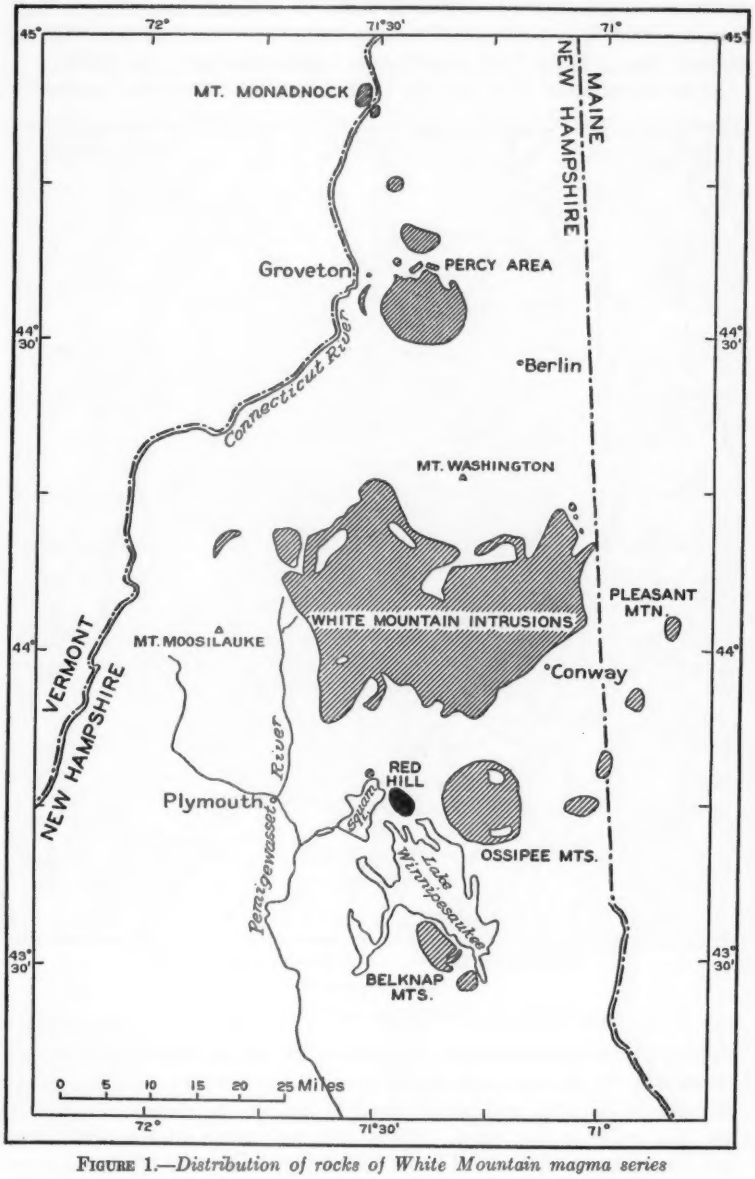


FIGURE 1.—*Distribution of rocks of White Mountain magma series*

northwest of the center, is separated from the southern summit by a sag. Garland Peak is a conical hill on the east side. Most of Red Hill is wooded, but at Eagle Cliff and Watson Ledge there are bare bluffs.

At an elevation of 1000 feet the trail, which leads from the southwest

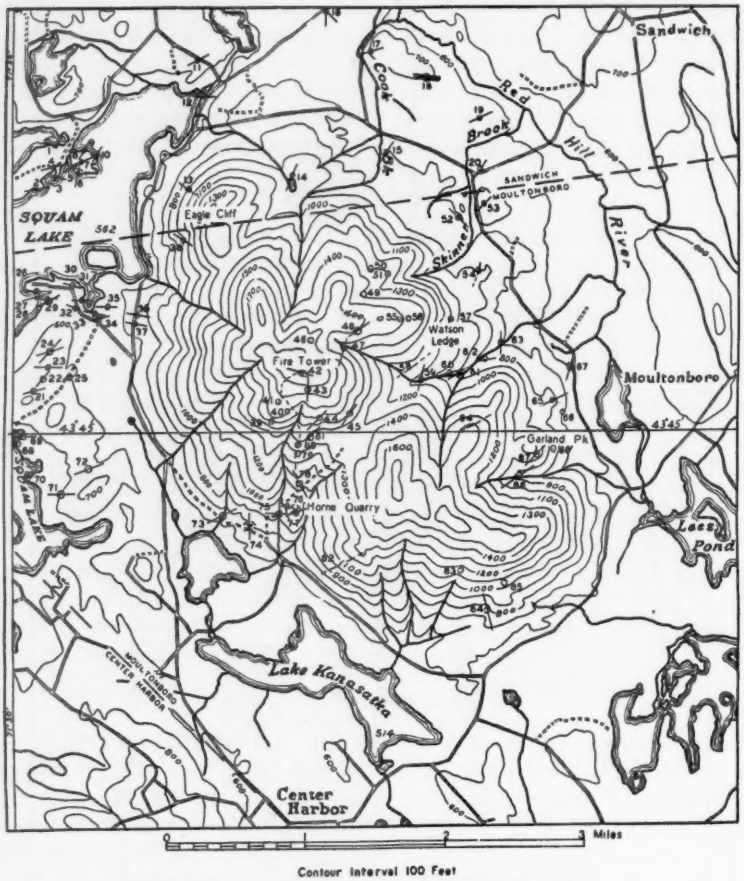


FIGURE 2.—*Topography and dikes of Red Hill*

side to the fire tower at the summit, passes the site of the old Horne house, mentioned by Pirsson and Washington in their report. At this point, it turns to the left, and an old road to the former Penniman place in the sag leads to the right. About 800 feet south of the site of the old Horne house, on a small knoll, are shallow pits—the "Horne quarry" —from which weathered nepheline-sodalite syenite was once removed for making roads. Comparatively fresh rock may be obtained at these pits.

OLDER ROCKS

GENERAL STATEMENT

All the older country rock, except a small area of amphibolite on

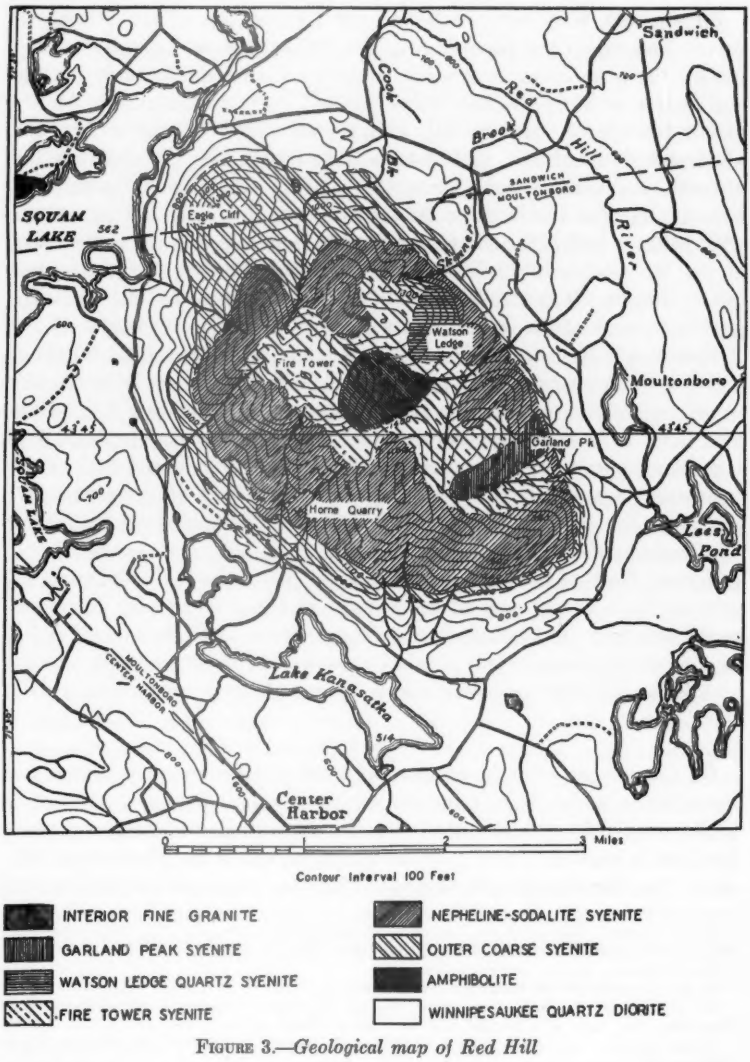


FIGURE 3.—*Geological map of Red Hill*

Long Point near the west edge of the map, is quartz diorite, which is included in the New Hampshire magma series and is known to be

intrusive into lower Devonian rocks.[3] The younger age limit is not known definitely, but Billings thinks these intrusions are of late Devonian age.[4]

WINNIPESAUKEE QUARTZ DIORITE

Pirsson and Washington followed the terminology of the Hitchcock survey and called the country rock the "Winnipesaukee gneiss." They stated: "It is an ordinary granitic gneiss consisting chiefly of orthoclase and quartz with considerable oligoclase and variable amounts of biotite and muscovite."[5] In the thin sections examined by the writer, the plagioclase is dominant, and there is little orthoclase; the rock has the mineralogical composition of a quartz diorite. Foliation is so faint in most places that the term gneiss seems hardly justified. In agreement with Billings and Althea Page Smith, who are mapping the older rocks of the Mt. Chocorua quadrangle, this rock is called the Winnipesaukee quartz diorite. It is a subdivision of what has been called the Chatham granite in some of the recent papers on New Hampshire geology.[6]

This rock is light- to medium-gray, is characterized by faint foliation, and is medium-grained, with grains 3-4 millimeters across. It is streaky in places, and many small pegmatite veins and aplite dikes cut it. Here and there it is somewhat porphyritic, with phenocrysts of plagioclase a centimeter or more in length. The quartz has pronounced undulatory extinction; some of the biotite flakes are bent; some of the plagioclase grains are bent and broken; but there is little crushing between the grains. The main mineral is andesine, about 38 to 40 per cent anorthite. It comprises from 57 to 75 per cent of the volume of the rock. Quartz constitutes 15 to 23 per cent of the volume of the rock and the biotite 10 to 20 per cent. Orthoclase is uncommon; there are a few small flakes of muscovite; magnetite is a fairly common accessory; apatite is common in large grains; and a few minute grains of zircon are present.

AMPHIBOLITE

On Long Point, near the northwest corner of the map is a small area of amphibolite, which is dark and irregularly streaky. Where weathered, it is characterized by rough pitted surfaces. It is composed largely of black hornblende crystals, up to 2 inches in length, and white plagioclase feldspar. The hornblende is the dominant mineral along the northern border,

[3] M. P. Billings: *Geology of the Littleton and Moosilauke quadrangles, New Hampshire*, State Planning and Development Comm., Concord (1935) p. 26-28.

[4] M. P. Billings: *personal communication.*

[5] L. V. Pirsson and H. S. Washington: *op. cit.*, p. 261.

[6] M. P. Billings: *Petrology of the North Conway quadrangle in the White Mountains of New Hampshire*, Am. Acad. Arts Sci., Pr., vol. 63 (1928) p. 82-83.

Louise Kingsley: *Cauldron-subsidence of the Ossipee Mountains*, Am. Jour. Sci., 5th ser., vol. 22 (1931) p. 154.

but the feldspar becomes dominant near the southern end of the point, just off the map. Many quartz veins cut the rock.

In thin-section the darker phases of the rock are seen to have the composition by volume: hornblende 74 per cent, labradorite 18 per cent, biotite 5 per cent, sphene 2 per cent, and rutile 1 per cent.

ROCKS OF THE WHITE MOUNTAIN MAGMA SERIES

GENERAL STATEMENT

The rocks that compose most of Red Hill belong to what has recently been termed the White Mountain magma series.[7] These rocks are younger than the Winnipesaukee quartz diorite, which is believed to be late Devonian. Billings,[8] who has determined these relationships, thinks the rocks of the White Mountain magma series were intruded in Carboniferous time, although the evidence is not yet decisive.

The Red Hill rocks that belong to the White Mountain magma series, will be described in order, from the outer margin to the interior, which is also the general order of their age, from the oldest to the youngest. The chemical composition and the norms of the plutonic rocks are given in Table 1. The modes are shown in Table 2. The optical properties of the amphiboles and the pyroxenes are given in Table 3.

The rock for analysis of the coarse outer syenite (Table 1, A) was obtained on the west side of Red Hill at an elevation of about 800 feet, in the bed of the brook that crosses the road junction a little more than half a mile north of the small pond just northwest of Lake Kanasatka. Rock for analysis of the feldspathoid-poor phase of the nepheline-sodalite syenite (Table 1, B) was obtained on the southwest side of the hill, at a small excavation just north of the abandoned road and about 800 feet northwest of the foot of the trail to the fire tower (Fig. 2, no. 74). It contains only a few small grains of feldspathoid. The excavation has slumped considerably since the rock was collected. Analysis C of Table 1 is from Pirsson's and Washington's paper[9] and represents the rock from the "Horne quarry." Analysis D is from Bayley's paper[10] and must be of an intermediate phase of the nepheline-sodalite syenite, although Pirsson and Washington thought it represented the fire-tower type. The exact location for this analysis is not known. The material for analysis E was taken from the fire warden's well about 150 feet southeast of the fire tower. The rock for the analysis of the Watson Ledge quartz syenite (F) came from near the southern end of the bluffs at Watson Ledge. The

[7] R. W. Chapman and C. R. Williams: *Evolution of the White Mountain magma series*, Am. Mineral., vol. 20 (1935) p. 502-530.

[8] M. P. Billings: *personal communication.*

[9] L. V. Pirsson and H. S. Washington: *op. cit.*, p. 273.

[10] W. S. Bayley: *op. cit.*, p. 250.

TABLE 1.—*Chemical analyses and norms of Red Hill plutonic rocks*

Chemical Analyses

Constituents	A	B	C	D	E	F	G	H
SiO_2	63.42	59.10	58.30	59.01	62.20	63.84	60.90	70.89
TiO_2	.18	.89	.10	.81	.34	.31	.47	.38
Al_2O_3	17.68	17.42	21.38	18.18	18.34	17.54	18.52	14.84
Fe_2O_3	1.80	2.50	1.05	1.63	1.01	1.88	1.41	.24
FeO	2.04	2.96	2.04	3.65	2.26	2.11	3.80	2.12
MnO	.05	.06	tr.	.03	.03	.03	.09	.06
MgO	.30	.99	.22	1.05	.42	.47	.92	.54
CaO	1.60	2.48	.95	2.40	2.32	.96	2.14	1.36
Na_2O	5.06	5.81	8.66	7.03	5.12	5.41	5.35	3.70
K_2O	7.64	6.92	6.06	5.34	7.01	7.07	5.75	5.50
H_2O+	.46	.52	.45	.50	.49	.43	.71	.42
H_2O-	.03	.04	.35	.15	.07	.10	.04	.03
CO_2	.....	.03	.....	.....	.....	.....	.....	.....
P_2O_5	.....	.09	.04	tr.	.11	.....	.02	.04
S	.01	.02	.....	.....	.04	.....	.03	.04
SO_3	.....	.....	.08	.....	.....	.....	.....	.....
BaO	.....	.06	none	.08	.06	.....	.09	.05
ZrO_2	.....	.09	.02	tr.	.14	.....	.....	.05
SrO	.....	.....	.....	tr.	.....	.....	.....	.....
Cl	.....	.12	.35	.12	.06	.....	.....	.....
Totals	100.27	100.10	100.05	99.98	100.02	100.15	100.24	100.26

Norms*

Constituents	Phlegrose I″.(4) 5.1″.3	Ilmenose (I)II .″5.1.3″	Miaskose I.6.1.″4	Umptekose (I)II.(4) 5.1.″4	Pulaskose I″.5.(1) 2.3	Phlegrose I″.5.1.3	Pulaskose I(II) .5.2.3″	Toscanose I″.4.(1) 2.3
Quarts	1.26	.....	.....	.....	.36	2.34	.....	23.10
Corundum	.....	.....	.....	.....	.....	.....	.....	.51
Zircon	.....	.18	.....	.....	.18	.....	.....	.....
Orthoclase	45.04	40.59	36.14	31.14	41.14	41.70	33.92	32.80
Albite	42.44	36.15	36.15	42.97	42.97	45.59	45.06	31.44
Anorthite	3.34	1.39	2.78	3.06	6.39	2.78	9.45	5.84
Nepheline	.....	6.82	18.74	8.24	.....	.....	.....	.....
Halite	.....	.12	.59	.23	.47	.....	.....	.....
Diopside	4.02	8.41	1.21	7.45	4.05	1.64	.92	.....
Hypersthene	.73	.....	.....	.....	1.69	2.22	6.39	4.44
Olivine	.....	.17	1.05	2.20	.....	.....	.27	.....
Magnetite	2.55	3.71	1.62	2.32	1.39	2.78	2.09	.23
Ilmenite	.43	1.67	.91	1.52	.61	.69	.91	.76
Apatite	.....	.34	.....	.....	.34	.....	.....	.34
Total	99.81	99.55	99.19	99.13	99.59	99.74	99.01	99.46

A—Outer coarse syenite. F. A. Gonyer, analyst.
B—Nepheline-sodalite syenite, feldspathoid-poor phase. F. A. Gonyer, analyst.
C—Nepheline-sodalite syenite, "Horne quarry." H. S. Washington, analyst.
D—Alkalic syenite of Bayley. W. F. Hillebrand, analyst.
E—Fire tower syenite, near fire tower at summit. F. A. Gonyer, analyst.
F—Watson Ledge quartz syenite, Watson Ledge. F. A. Gonyer, analyst.
G—Garland Peak syenite, top Garland Peak. F. A. Gonyer, analyst.
H—Interior fine granite. F. A. Gonyer, analyst.
* Norms C and D recalculated. Pirsson and Washington modified these norms to include sodalite.

sample of Garland Peak syenite (G) was taken from near the top of Garland Peak. The specimen for the interior fine granite (H) was taken

TABLE 2.—*Modes of the Red Hill plutonic rocks*

Constituent	Per cent by volume					
	A	B	C	D	E	F
Quartz	.....	.....	.....	4–6	3	16–19
Microperthite	80–85	60–80	85–90	80–90	77	60–70
Plagioclase	.....	.....	.....	.....	9	8–13
Nepheline	.....	0–31 } 0–34	.....	.....	.....	.....
Sodalite	.....	0–30 }	.....	.....	.....	.....
Amphibole	15–20	6–15	10–15	6–10	10	1–2
Aegirinaugite	0–5	0–5	.....	.....	.....	.....
Biotite	.....	.....	.....	1–2	1	6–8

A—Outer coarse syenite.
B—Nepheline-sodalite syenite.
C—Fire Tower syenite.
D—Watson Ledge quartz syenite.
E—Garland Peak syenite.
F—Interior fine granite.

from the north-central part of the granite mass in the brook, at an elevation of about 1200 feet.

AREAS OF OUTCROP

The areas of outcrop of the main types of plutonic rocks of Red Hill are given in Table 4. The total area of the plutonic types of the White Mountain magma series, as given by Chapman and Williams,[11] and excluding certain unmapped areas, is 457.78 square miles. The Red Hill rocks, therefore, constitute about 1.4 per cent of the whole as now known.

OUTER CONTACT OF THE RED HILL ROCKS

As stated by Pirsson and Washington,[12] the exact contact of the Red Hill rocks with the Winnipesaukee quartz diorite is not exposed. At a few places where outcrops are fairly close to the contact, there is no indication of either endomorphic or exomorphic effect. Near the outer contact, there is greater tendency for the syenite to be coarse than to be fine. The pegmatitic and aplitic phases in the quartz diorite, which Pirsson and Washington thought to be contact phenomena, seem to be as abundant away from the contact as near it, and they are, therefore, considered to be related to the quartz diorite intrusion rather than to the igneous activity of Red Hill.

[11] R. W. Chapman and C. R. Williams: *op. cit.*, p. 507.
[12] L. V. Pirsson and H. S. Washington: *op. cit.*, p. 262.

TABLE 3.—*Optical properties of amphiboles and pyroxenes*

	1	2	3	4	5	6	7	8	9
Indices ±.001 α	1.696	1.694	1.695	1.689	1.697	1.693	1.675	1.726	1.700
Indices ±.001 β	1.713	1.711	1.711	1.707	1.713	1.713	1.700	1.731	1.710
Indices ±.001 γ	1.714	1.712	1.713	1.708	1.714	1.714	1.707	1.751	1.723
Sign	−	−	−	−	−	−	−	+	+
2V	small (10°–20°)	small	small	small	small	small	moderate	large	large
Dispersion	strong r<v	strong r<v	strong r<v	strong r<v	strong r<v	strong r<v	distinct r<v	distinct r>v	moderate r>v
Orientation	β=b	γ=b	β=b	β=b	β=b	β=b	β=b	β=b	β=b
Maximum extinction angle in vertical zone	25°	29°	33°	25°	25°	28°	31°	58°	40°
Pleochroism X	light yellowish brown	light yellowish brown	light yellowish brown	light brown	light brown	light yellow	light yellow	dark green	faint green
Pleochroism Y	greenish brown	dark olive green	greenish brown	greenish brown	brownish green	brownish green	brownish green	clear green	faint green
Pleochroism Z	dark green	dark green	brownish green	dark green	dark green	dark green	dark green	light brownish yellow	faint green
formula	Z≧Y>X	Z≧Y>X	Z=Y>X	Z>Y>X	Z>Y>X	Z>Y>X	Z>Y>X	X>Y>Z	Y>X=Z

1. Hastingsite from outer coarse syenite.
2. Hastingsite from nepheline-sodalite syenite at the "Horne quarry."
3. Hastingsite from fire tower syenite at well near summit.
4. Hastingsite from Watson Ledge quartz syenite.
5. Hastingsite from amphibole pegmatite near Watson Ledge.
6. Hastingsite from Garland Peak syenite.
7. Hornblende from interior fine granite.
8. Aegirinaugite from near outer edge of nepheline-sodalite syenite.
9. Diopside-hedenbergite from outer coarse syenite near north end of Red Hill.

OUTER COARSE SYENITE

The syenite exposed on the north end of Red Hill probably forms a border around the whole hill. It is generally weathered so that entirely fresh specimens are difficult to obtain, even at such extensive exposures as the bluffs at Eagle Cliff. The rock is characterized especially by variability of texture. In general, however, it has a rather even mineral

TABLE 4.—*Areas of Red Hill plutonic rocks*

	Square miles	Per cent
Outer coarse syenite	1.48	23.9
Nepheline-sodalite syenite	2.89	46.7
Fire tower syenite	1.27	20.5
Watson Ledge quartz syenite	.14	2.3
Garland Peak syenite	.18	2.8
Interior fine granite	.24	3.8
	6.20	100.0

composition and consists of about 80 to 85 per cent by volume microperthite and about 15 to 20 per cent amphibole. The smaller grains are about 1 to 1½ centimeters in size, but there is much pegmatitic material, with grains up to 5 or 6 centimeters in length. This coarse pegmatitic phase seems to be most abundant near the outer contact with the Winnipesaukee quartz diorite. In large exposures, such as those at Eagle Cliff, the pegmatitic material is distributed as irregular streaks, patches, and veins. In some places, it occupies large areas, and many of the smaller outcrops consist only of pegmatite.

The amphibole of this rock seems to be a hastingsite, as is indicated by the optical properties of the most common type (Table 3, no. 1). Amphibole with approximately these properties is present from Skinner Brook around the north end of Red Hill and south almost to Lake Kanasatka. Variations from these properties are found and are toward lower indices, with other properties similar. Thus, the amphibole in the small valley just north of Garland Peak has indices: $\alpha = 1.674$, $\beta = 1.696$, $\gamma = 1.697$, and just north of Lake Kanasatka the amphibole has the following indices: $\alpha = 1.684$, $\beta = 1.701$, $\gamma = 1.702$. So far as can be determined, these do not belong to different intrusions, but are variations in one intrusive body, although relations around the south and east sides of Red Hill are not well revealed.

In certain thin-sections, aegirinauguite forms up to 5 per cent. Some of the grains have outer shells of amphibole, probably hastingsite.

Small amounts of quartz are visible, but it apparently never composes more than 5 per cent of the rock, and usually it is to be seen only in scattered grains, if at all. Biotite is present in small amounts as an alteration product from the amphibole. Sphene is an abundant accessory; other accessories are zircon, apatite, and magnetite.

What appears to be a small irregular intrusion into the outer coarse syenite is exposed in a small quarry a few hundred feet north of the pond near the north end of Red Hill. It is a coarse (grains are 1 to 1½ centimeters in size), dark-gray rock, consisting of, by volume, microperthite 73 per cent, biotite 18 per cent, and pale-green pyroxene 7 per cent. The optical properties of the pyroxene indicate that it belongs to the diopside-hedenbergite series (Table 3, no. 9). There is also considerable apatite and magnetite.

Another irregular minor intrusion cuts the outer coarse syenite at an elevation of 700 feet, in the bed of the brook just east of the main trail to the fire tower. The rock is too much weathered to yield material suitable for careful study, but it is apparently a fine syenite, composed of lath-shaped feldspars, which are oriented parallel to the contact, and a dark mineral, now replaced by needle-like masses of limonite, which was probably an amphibole.

NEPHELINE-SODALITE SYENITE

The nepheline-sodalite syenite that forms an irregular ring inside the coarse outer syenite is, like the outer syenite, a variable rock. The texture is perhaps less variable than that of the outer syenite, but the mineral composition is more variable. These variations are on a small scale and are rather unsystematic, although the feldspathoids seem to be generally less abundant near the outer and the inner margins of the mass. The outer feldspathoid-poor border is narrow in most places and at others is absent. The rock in the "Horne quarry" is typical; Pirsson's careful petrographic description and Washington's chemical analysis are of this rock.[13]

The rock is medium-grained, with crystals varying from 2 to 10 millimeters, and averaging about 4 millimeters. The color is light-gray to gray. The feldspars are usually lath-shaped and show carlsbad twinning. The nepheline is greasy and gray to light-brown. The sodalite is greasy and gray to greenish or faint bluish. The amphibole is in black stubby crystals. There are some flakes of biotite. On weathering, the sodalite and nepheline generally recede in such a way as to reveal the abundance of the feldspathoids.

Studies of thin-sections and of weathered surfaces indicate that the feldspar constitutes 60 to 80 per cent of the volume of the rock. It is practically all perthitic, generally in a fashion termed "interdented" by Pirsson and Washington.[14] Their description of this texture is, in part:

"The albite lamellae of the microperthite intergrowths of one crystal extend out in optical continuity and project into neighboring crystals, often enlarging as they do so and forming knobs or hooks."

[13] *Op. cit.*, p. 266-274.
[14] *Op. cit.*, p. 272.

Some of the albite lamellae are enlarged to the extent of forming shells of albite around the microperthite. It is of the type termed "deuteric" by Alling.[15] The albite lamellae extend not only into other feldspar grains, but also into amphibole crystals. If the albite bands were formed by replacement along contraction cracks, in the manner suggested by Andersen,[16] it would appear that the replacement extended even into the amphibole. The replacing solutions would have most access to the amphiboles along the continuation of the feldspar fractures, would replace the amphibole there, and might leave the intervening amphibole unreplaced, as appears to have been done here. Pirsson and Washington attribute the texture to "local pneumatolytic conditions producing a more nearly simultaneous process of crystallization of all these minerals."

The optical properties of the amphibole (Table 3, no. 2) agree rather closely with those of the hastingsite group,[17] and the analysis of the rock seems to agree with that conclusion.

A few grains of aegirinaugite are found in the outer feldspathoid-poor phases of this rock (Table 3, no. 8); it may constitute as much as 5 per cent of the rock.

Nepheline is a variable constituent of this rock; Rosiwal determinations on thin-sections yield up to 31 per cent. The variability may be either because sodalite constitutes almost the whole of the feldspathoid content of the rock or because there is little feldspathoid. In some specimens, the nepheline is brownish and may be distinguished from the gray sodalite without great difficulty, but commonly it is difficult to distinguish between the two feldspathoids on the basis of appearance. In thin-sections the nepheline is seen to be in large grains, most of which show rough crystal outlines. The boundary of a nepheline grain may be a crystal face of microperthite, but, more commonly, a crystal face of nepheline cuts obliquely across the microperthite. Many of the nepheline grains show concentric growth lines, with the crystal faces parallel to the growth lines. These relationships might indicate either that the nepheline crystallized from the magma earlier than the microperthite, or that it was formed by a later non-selective replacement. As already stated, in the microperthite the albite has a tendency to be more abundant along the edges of the crystals and even to form shells around them. That tendency seems to be developed along the boundaries of the nepheline. Therefore, it appears that the nepheline was present when the perthitic intergrowth was formed. Such a situation would almost certainly exist

[15] H. L. Alling: *Perthites*, Am. Mineral., vol. 17 (1932) p. 54-55, 57, 58.

[16] Olaf Andersen: *The genesis of some types of feldspar from granite pegmatites*, Norsk. Geol. tidsskr., B. 10, h. 1-2 (1928) p. 116-205.

[17] M. P. Billings: *The chemistry, optics, and genesis of the hastingsite group of amphiboles*, Am. Mineral., vol. 13 (1928) p. 283-289; Table I, b.

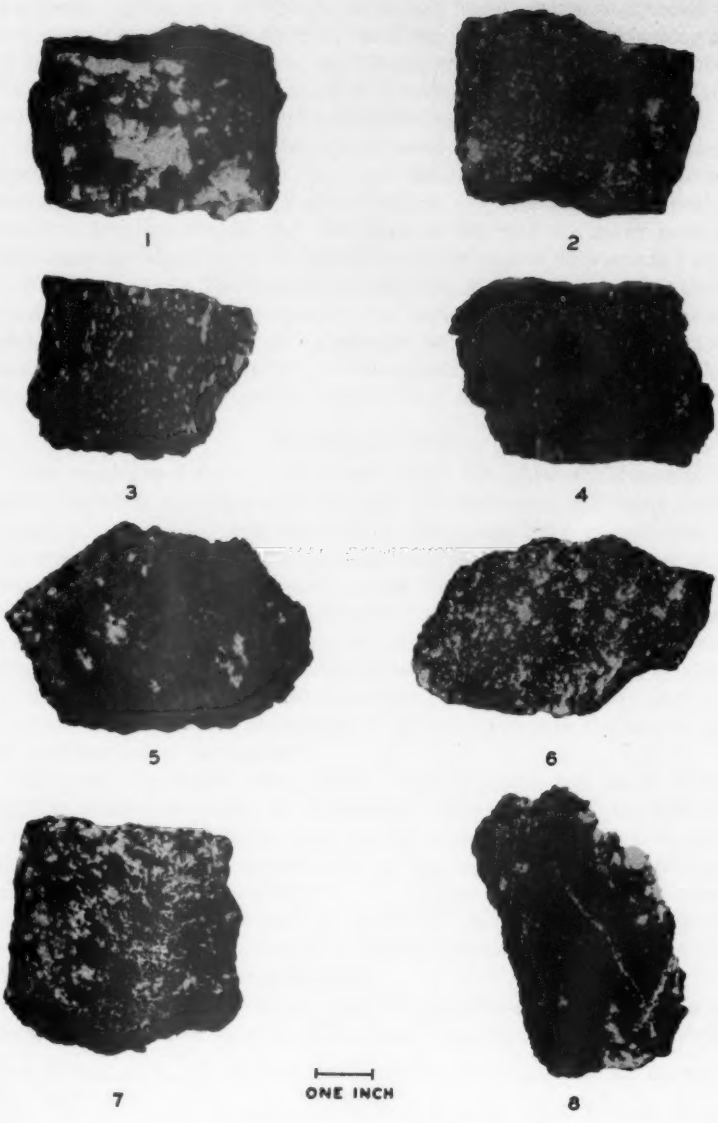
if the nepheline were formed as an early magmatic mineral; it might or might not exist if the nepheline were formed by replacement, for the perthite may be formed by replacement, and it is not known which replacement would take place first. The absence of anything that might be interpreted as unreplaced remnants of older minerals in the nepheline seems to favor the conclusion that the nepheline is an earlier magmatic mineral.

Sodalite is grayish or greenish- to bluish-gray, and is almost identical in appearance to the nepheline, except where the nepheline has a distinctive faint brownish cast. Both the sodalite and the nepheline weather more readily than do the other minerals of this rock, and the total feldspathoid content of the rock can be readily determined on weathered faces. It generally does not amount to more than 30 per cent. The sodalite may be easily distinguished from the other minerals by its fluorescence in ultra-violet light. A "Nico" tube was used in laboratory study of the rock. In the field, ultra-violet light was obtained from the sun by use of a Red Purple Ultra #597 Corning filter.

Optical and chemical tests showed the sodalite to be relatively pure, with perhaps a small amount of hackmanite. The index of refraction is 1.483 (± .002). It is perhaps the most variable constituent of the rock, as may be seen by the photographs of the fluorescent sodalite[18] (Pl. 1). Specimens 1, 2, 3, 5, and 6 are from the "Horne quarry"; 7 and 8 are from the northeast side of Red Hill; and 4 is from the small excavation near the road, about 800 feet northwest of the foot of the trail to the fire tower. The great variability in the amount, in the grain-size, and in the relationships, is obvious. Photographs 1 and 2 are different sides of a hand specimen. Much of the sodalite has somewhat the same textural relationships as have the other minerals, but, in specimen 8, it is definitely in veinlets, and, in specimen 3, most of the sodalite is in part of a dike. Specimen 4 is of a feldspathoid-poor phase of this rock. Thin-sections show the sodalite to be interstitial, and, to some extent, it appears to replace other minerals. Field relations indicate that the sodalite is concentrated in dikes and irregular streaks—parts of the rock that solidified last. These relationships show clearly that the sodalite was, in part at least, a late mineral in the crystallization. Probably some of it had a deuteric or a hydrothermal origin.

A few grains of biotite are to be found in most slides, mainly as alterations of the amphibole. A small amount of cancrinite is present as alterations of the feldspathoids. Sphene, apatite, and zircon are present as accessories. Newhouse identified the opaque minerals of this rock as

[18] Alonzo Quinn: *A petrographic use of fluorescence.* Am. Mineral., vol. 20 (1935) p. 466-468.



FLUORESCENT SODALITE

Fluorescent sodalite (white), feldspar and nepheline (gray), and amphibole (black).

magnetite, pyrite, and pyrrhotite;[19] he also found magnetite-ilmenite in a fine-grained phase. Woehlerite was found by Pirsson and Washington in blocks on a stone wall near the "Horne quarry".[20] Nothing can here be added to their description of this mineral except that some thin-sections of the "Horne quarry" rock contain one or more grains.

A finer-grained phase of the nepheline-sodalite syenite crosses the fire-tower trail between the 1400-foot and the 1500-foot contour lines and extends northwestward and a short distance southeastward. The grains are 2 to 3 millimeters in size. Included in this rock are many patches and vague streaks of biotitic nepheline-sodalite syenite with grains 1 to 3 millimeters across. The biotitic rock, especially, has many honey-yellow grains of sphene. Microscopically, the texture appears to be irregular and "ragged" in appearance. There are many small needles of apatite and some plagioclase. Nothing definite could be learned about the relationship of this rock to the rest of the nepheline-sodalite syenite.

FIRE TOWER SYENITE

The syenite that forms a large area inside the feldspathoid syenite is well exposed on the main summit under the fire tower, and fairly fresh material was obtained from the ranger's well, about 150 feet southeast of the tower. This rock is more uniform than is the feldspathoid syenite. The writer believes it is the rock named "hornblende-tracho-umptekose, umptekite" by Pirsson and Washington[21] and is, according to them, the rock described by Bayley. However, so far as can be determined from Bayley's description, the rock he described came from a different locality on Red Hill. Furthermore, the characteristics given by Bayley and the analysis by Pirsson and Washington[22] do not agree with the characteristics of the rock at the summit.

The rock is generally light pinkish, gray in places, and has a fairly uniform grain-size of 3 to 4 millimeters. Megascopically, the rock is composed of pinkish feldspar, black stubby amphibole crystals, and some biotite flakes. In the western part of the sag between the northwest and the southeast summits, the rock has visible quartz grains, but elsewhere it has neither quartz nor feldspathoids. Near the fire tower, there are many closely spaced joints, but the trachytoid texture mentioned by Pirsson and Washington was not seen.

Microscopically, the grains interlock in a complicated fashion, giving a "ragged" appearance. Microperthite constitutes about 85 to 90 per cent

[19] W. H. Newhouse: *Opaque oxides and sulphides in common igneous rocks*, Geol. Soc. Am., Bull., vol. 47 (1936) p. 1-52.

[20] L. V. Pirsson and H. S. Washington: *Contributions to the geology of New Hampshire; No. 3, On Red Hill, Moultonboro*, Am. Jour. Sci., 4th ser., vol. 23 (1907) p. 270-271.

[21] *Op. cit.*, p. 273-276.

[22] *Op. cit.*, p. 273, analysis No. 2.

of the volume of the rock. Carlsbad twins with irregular junction lines are common. The amphibole, which composes 10 to 15 per cent of the rock, seems to have the optical properties of the hastingsite group (Table 3, no. 3). Biotite is present, but not common; magnetite, apatite, and sphene are fairly common as accessories, and one grain of allanite was seen.

The relations of the fire-tower syenite to the nepheline-sodalite syenite are not clear, but there seems to be a gradational contact. The fire-tower syenite is definitely older than the other rocks with which it is in contact.

WATSON LEDGE QUARTZ SYENITE

The rock of the prominent bluffs known as Watson Ledge was at first considered to be a phase of the fire-tower syenite, but field relations seem to indicate that the Watson Ledge rock was intruded into the syenite. The evidence for this is mainly that the Watson Ledge quartz syenite is porphyritic along its contact with the syenite and that this porphyritic phase contains many inclusions of syenite and of a fine-grained basic rock.

The grains in this rock are 3 to 4 millimeters in size. In the porphyritic phase, the feldspar phenocrysts are about the same size, and the groundmass is much finer. This rock is more grayish than is the fire-tower syenite. There are many small coarse streaks, with amphibole and rather large grains of quartz clustered together. These clusters somewhat resemble miarolitic cavities. Many of the quartz crystals have a few prism faces; some of the quartz seems to be interstitial, also.

Rosiwal determinations on this rock are not very dependable because of the irregular distribution of the quartz and amphibole, but the approximate proportions by volume are: microperthite, 80 to 90 per cent; amphibole, 6 to 10 per cent; biotite, 1 to 2 per cent; and quartz, 5 per cent. The microperthite is similar to that in the fire-tower syenite. The amphibole has somewhat lower indices of refraction than do the amphiboles in the rocks previously described, but it is otherwise similar, and is probably a member of the hastingsite series (Table 3, no. 4). The biotite is strongly pleochroic, with Y and Z dark-green and X orange-brown, $Y = Z > X$. Magnetite and zircon are abundant accessories.

AMPHIBOLE PEGMATITE

Around the northeast edge of the Watson Ledge quartz syenite, and parallel to the contact between it and the nepheline-sodalite syenite, is a zone of amphibole pegmatite. Rarely is it found in place, but large blocks of it are so common along the contact that there can be little doubt that it is in place there. It consists of large blades of amphibole up to 6 centimeters in length and 2 centimeters in width, microperthite,

and a small amount of quartz. In places, the amphibole is arranged in radial fashion; its optical characters indicate that it is in the hastingsite series (Table 3, no. 5).

GARLAND PEAK SYENITE

The Garland Peak syenite is best exposed on Garland Peak, but numerous outcrops of it may be seen in the area southwest of the peak.

This rock is light- to dark-gray and is, in places, yellowish from weathering. Most of the feldspar grains are less than one millimeter in length. The most striking feature of the rock is the presence of many needle-like grains of amphibole, some of the needles as much as 4 millimeters long. Near the margins of the mass the amount of amphibole increases somewhat, giving the rock a darker appearance.

The most abundant type of the rock consists of about 77 per cent microperthite, 10 per cent amphibole, 9 per cent plagioclase, 3 per cent quartz, and 1 per cent biotite, all by volume. The texture is irregular; the microperthite, especially, is in irregular grains. The amphibole is in long crystals with irregular edges. The optical properties relate it to the other hastingsites here (Table 3, no. 6). Plagioclase, of oligoclase composition, is present in zoned grains somewhat larger than most of the other grains. Quartz occupies fairly large interstitial areas. The biotite seems to be the result of alteration of the amphibole. Minute apatite needles are abundant as an accessory; zircon and magnetite are also present.

The general relations of the body suggest that it is intrusive into the fire-tower syenite and the feldspathoid syenite. Further evidence that it is younger than the fire-tower syenite is the fact that, near the contact, just south of the top of Garland Peak, there is a 5-foot inclusion of the fire-tower syenite in it. There seems to be no opportunity for determining whether this rock is older or younger than the interior fine granite.

INTERIOR FINE GRANITE

East of the fire tower is a small oval body of fine-grained granite. The small valley leading northeastward from the sag has many excellent exposures of this rock, and at several of them it is possible to obtain fairly fresh material.

This granite is light-gray to faintly pinkish, where fresh, and slightly yellowish where weathered. The grain-size is about 1 to 2 millimeters and is fairly uniform. There are a few scattered feldspar crystals up to 4 millimeters. Clusters of biotite up to 4 millimeters are also present. A casual observation might fail to reveal the quartz, which is in small grains.

Rosiwal determinations indicate that the rock has the following composition by volume: microperthite, 60 to 70 per cent; plagioclase, 8 to 13 per cent; quartz, 16 to 19 per cent; biotite, 6 to 8 per cent; and amphi-

bole, 1 to 2 per cent. Microscopically, the texture is highly irregular, with large irregular feldspar grains and small round quartz grains. The biotite and amphibole are intermediate in size to the feldspar and quartz. The microperthite is both in large carlsbad twins with irregular suture lines and in small grains intergrown with quartz. A few inclusions of plagioclase are in the microperthite. The plagioclase is zoned and has somewhat better-developed crystals than has the microperthite; it is oligoclase, about 20 per cent anorthite. The amphibole, which is different from the others at Red Hill (Table 3, no. 7), is probably a hornblende.[23] Biotite is in irregular grains; the index of refraction on flakes of it is about 1.673 (±.002), although it varies.

Only in the stream bed at the northeast margin of the granite mass is the contact with the fire-tower syenite exposed. There, it descends to the northeast by steps, giving the impression of a "blocky" roof, such as is supposed to be produced by stoping. The granite is definitely younger than the syenite. The present oval outcrop appears to be the top of an intrusive body, and, if erosion had cut more deeply, the outcrop of the granite would probably be much more extensive.

DIKES

Dikes of several kinds are abundant in the region; Pirsson and Washington devoted the second part of their paper [24] to a discussion of the main types. The writer found about a hundred dikes; their locations are indicated in Figure 2. Probably there are many more than were seen. They seem to be most abundant northwest of Red Hill, between it and the related syenite body at The Rattlesnakes, in the Plymouth quadrangle to the west. About 25 thin-sections of the dike-rocks were studied, and crushed material from certain other dikes was examined. Many of them are not well exposed, and it is not possible to obtain fresh material for study. It was not thought worth while to make careful descriptions of all the dikes, but brief descriptions of the types are given. Table 5 gives the name, strike, dip, and thickness, insofar as they have been determined.

Camptonite is the most common type of dike in this district. The main minerals are brown amphibole and plagioclase feldspar. The amphibole is generally in long phenocrysts; some augite and biotite are present. Chloritic alterations are common; calcite is found as an alteration and as vesicular fillings. All these trap dikes are dark and fine-grained, and it is generally impossible to distinguish between them except in thin-section.

The kersantites differ from the camptonites mainly by having biotite

[23] R. W. Chapman and C. R. Williams: *Evolution of the White Mountain Magma series*, Am. Mineral., vol. 20 (1935) Tables 7 and 8, no. 5.

[24] L. V. Pirsson and H. S. Washington: *op. cit.*, p. 433-447.

as the dominant dark mineral; the vogesites differ from the camptonites mainly by having orthoclase instead of plagioclase.

There is one diorite dike on the hill just west of Garland Peak. Its texture and mineral composition are variable. The main minerals are andesine and hornblende, the andesine being somewhat the more abundant; orthoclase is also abundant. Much of the hornblende has partially altered to biotite.

Syenite porphyry is the most common type of salic dike; it is usually pink, yellowish, or gray, and there is generally only a suggestion of the trachitic texture. The main mineral is potash feldspar, which is commonly perthitic. Some phenocrysts of plagioclase, and small amounts of interstitial quartz may be found. Amphibole having the appearance of hastingsite is common, and some specimens have small flakes of biotite.

The paisanite dike in the "Horne quarry" was described at some length by Pirsson and Washington.[25] Microperthite is the most abundant mineral, quartz is one of the main constituents, and riebeckite is the most common dark mineral, although the dike at the "Horne quarry" has almost as much aegirite.

A few tinguaite dikes were found, the main constituents being orthoclase and the feldspathoids, nepheline and sodalite. The feldspar is in laths and displays the trachytic texture, considerable aegirite is present, and there is also a small amount of biotite and riebeckite.

The trap dikes—lamprophyres—are more abundant than are the salic dikes. In three places where the intersection of dikes was seen, one of which is in the Plymouth quadrangle, the lamprophyre was younger than the salic dike.

The salic dikes, in general, trend eastward, the strike ranging from N 60° W to S 45° W. The lamprophyres are less restricted, but also strike in a general eastward direction, between N 75° W and S 15° W.

STRUCTURAL AND AGE RELATIONSHIPS

The coarse outer syenite forms at least a partial ring around the interior bodies. However, its presence all along the outer contact is not certain. The main reason the map was drawn to show a complete ring is that there are several places, such as those just southeast of Skinner Brook, east of Garland Peak, and along the southern border, where a narrow band of the coarse outer syenite is present.

The nepheline-sodalite syenite appears to be younger than the outer coarse syenite, for there are intrusions of the feldspathoid syenite in the outer coarse syenite and the feldspathoid syenite is banded against the syenite. There is a small dike of the feldspathoid syenite in the

[25] *Op. cit.*, p. 438-443.

TABLE 5.—*List of dikes*

No.*	Type	Strike	Dip	Thickness Feet	Thickness Inches
1	camptonite	N 85° W	90° ±	3	..
	salic	N 80° W	.....	3	9
	paisanite	N 80° W	.....	3	4
2	syenite porphyry	N 80° E	90° ±	15	..
3	lamprophyre	N 80° W	90° ±	1	6
4	syenite porphyry	N 75° E	90° ±	1	..
5	lamprophyre	N 65° E	90° ±	1	..
	lamprophyre	N 73° W	90° ±	1	..
6	kersantite	N 12° E	64° W	3	..
7	syenite porphyry	N 69° E	90 ±	7	..
8	kersantite	N 20° E	.....	25+	..
9	lamprophyre	N 30° E	90° ±	..	..
10	lamprophyre	N 30° E	90° ±	..	..
11	lamprophyre	N 64° E	90° ±	1	8
12	kersantite	N 90° E	90° ±	..	9
	kersantite	N 90° E	90° ±	2	8
13	syenite porphyry	N 55° W	90° ±	..	..
14	camptonite	N 20° E	90° ±	..	4
15	kersantite	N 33° E	90° ±	2	2
16	camptonite	N 45° W	90° ±	6	..
	lamprophyre	N-S	90° ±	..	..
17	syenite porphyry	N 75° E	90° ±	15	..
	kersantite.....boulders by road	.....	.....	..	..
18	lamprophyre	N 83° W	90° ±	4+	..
	syenite porphyry	N 83° W	90° ±	25	..
	syenite porphyry	N 83° W	90° ±	7	6
	salic	N 83° W	90° ±	1+	..
19	syenite porphyry	N 65° E	90° ±	5	..
20	vogesite	N 35° E	55° W	..	9
21	salic	N 75° E	.....	..	..
22	quartz syenite porphyry	N 40° E	90° ±	large	
23	vogesite	N 90° E	90° ±	2	..
24	intersecting dikes	.....	.....	..	..
	syenite porphyry	N 43° E	90° ±	1	2
	kersantite (younger)	N 72° E	90° ±	3+	..
25	tinguaite	.....	.....	..	..
26	camptonite	N 90° E	90° ±	3	..
	camptonite	N 90° E	90° ±	3	..
27	camptonite	N 75° E	55° N	2	6
28	syenite porphyry	N 90° E	68° N	5	..
29	salic	N 65° E	90° ±	15	..
30	camptonite	N 75° W	90° ±	4	..
31	salic	N 85° W	90° ±	8	..
	kersantite	N 63° E	90° ±	2	..
	lamprophyre	N 85° W	90° ±	1	6
	intersecting dikes	.....	.....	..	..

* Numbers refer to locations on Figure 2.

TABLE 5.—*List of dikes (continued)*

No.*	Type	Strike	Dip	Thickness Feet	Inches
	salic	N 30° E	90° ±	3	..
	lamprophyre (younger)	N 63° E	90° ±	3	..
32	tinguaite	N 72° W	90° ±	1	..
33	lamprophyre	N 80° W	90° ±	1	6
34	lamprophyre	N 78° E	90° ±	1	6
35	salic	N 90° E	90° ±	3+	..
36	tinguaite	N 80° W	90° ±	5+	..
37	lamprophyre	N 80° W	90° ±	1	6
38	paisanite	N 60° W	90° ±	6+	..
39	camptonite	.....	.....	2+	..
40	lamprophyre	.....	.....	..	..
41	lamprophyre	.....	.....	..	..
42	kersantite	N 75° W	90° ±	12	..
43	camptonite	N 3° E	90° ±	3	1
44	lamprophyre	N 45° E	90° ±	8+	..
45	kersantite	N 35° E	65° E	5+	..
46	lamprophyre	.....	.....	..	..
47	lamprophyre	N 15° E	90° ±	6+	..
48	lamprophyre	N 55° E	90° ±	4+	..
49	lamprophyre	.....	.....	..	..
50	kersantite	.....	.....	10+	..
51	lamprophyre	.....	.....	..	..
52	lamprophyre	N 45° W	90° ±	1	..
53	camptonite	N 48° E	90° ±	2	..
	lamprophyre	N 48° E	90° ±	..	8
54	lamprophyre	.....	.....	2	6
55	lamprophyre	.....	low	..	..
56	lamprophyre	.....	.....	..	..
57	lamprophyre	.....	.....	..	..
58	syenite porphyry	.....	.....	100+	..
59	lamprophyre	N 15° E	90° ±	7	..
60	camptonite	N 75° E	90° ±	..	4
61	paisanite	N 60° E	90° ±	..	6
62	kersantite	.....	.....	..	..
63	kersantite	N-S	90° ±	..	..
64	diorite	.....	90° ±	20+	..
65	camptonite	N 65° E	90° ±	..	4
66	lamprophyre	.....	.....	..	..
67	kersantite	N 15° E	90° ±	1	6
68	salic	.....	.....	..	..
69	lamprophyre	N 90° E	90° ±	3	..
70	lamprophyre	.....	.....	..	..
71	salic	N 90° E	.....	..	..
72	camptonite	N 70° E	90° ±	6	..
73	camptonite	N 63° E	90° ±	2	8+
	camptonite	N 63° E	90° ±	2	8

TABLE 5.—*List of dikes (continued)*

No.*	Type	Strike	Dip	Thickness	
				Feet	Inches
74	camptonite	N-S	90° ±	..	8
	camptonite	N-S	90° ±	..	8
75	syenite porphyry	N 90° F	90° ±	5	..
76	lamprophyre	.....	.....	..	..
77	paisanite	N 73° E	90° ±	1	..
78	kersantite	N 30° W	90° ±	..	..
79	camptonite	.....	.....	..	..
80	lamprophyre	.....	.....	..	..
81	camptonite	N 45° E	.....	25+	..
82	lamprophyre	.....	.....	..	..
83	lamprophyre	.....	.....	..	..
84	lamprophyre	N 15° W	.....	3+	..
85	lamprophyre	.....	.....	..	..
86	lamprophyre	N 55° E	25° E	5+	..
87	lamprophyre	.....	.....	4+	..
88	syenite, Garland Peak type	.....	.....	2	..

outer coarse syenite near the northwest end of Red Hill, and the nepheline-sodalite syenite in the small excavation 800 feet northwest of the foot of the trail appears to be an irregular intrusion into the coarse syenite. The banding of the feldspathoid syenite against the outer coarse syenite is especially developed on the northeast side of Red Hill, just south of Skinner Brook.

The relationships of the nepheline-sodalite syenite to the fire-tower syenite are not entirely clear. Probably, the contact between them is gradational, with feldspathoids becoming less abundant and the texture becoming more even near the inner edge of the feldspathoid syenite.

The shape of the interior bodies—the Watson Ledge quartz syenite, the Garland Peak syenite, and the interior fine granite—indicates that they are younger than any of the other rocks. Further evidence is given by the porphyritic border of the Watson Ledge quartz syenite, by the inclusion of fire-tower syenite in the Garland Peak syenite, and by the exposed contact of the interior fine granite in the brook at the northeast edge of the granite body. There seems to be no way to determine the age relations of these interior intrusions to one another. In general, each rock mass seems to be younger than the adjacent outer rock and older than the adjacent interior rock.

The concentric arrangement of the different types of rock, which is the most striking thing shown by the map, suggests the possibility that the outer coarse syenite and the nepheline-sodalite syenite are ring-dikes, a type of structure that is well developed in other intrusions of the White

Mountain magma series.[26] There are other types of concentric structure, however, and a ring-like mass of rock cannot be proved to be a ring-dike unless it is shown that the mass took the ring shape when it was intruded. Normally, the ring should be younger than both the rock on the exterior and that in the interior, but examples are known where at least a part of the rock enclosed by the ring-dike has been displaced by younger intrusions. One example is the Ossipee Mountains ring-dike, where a large part of the interior area is occupied by younger Conway granite. If the whole of the interior mass had been displaced by the younger rock, it would be difficult, indeed, to determine that the intrusion was a ring-dike. The only proof that would remain under such circumstances would be chilled borders or other contact phenomena along the interior margin of the ring. Such evidences appear to be absent from the coarse outer syenite, and there is no evidence, except the shape, for calling it a ring-dike. The crude ring of nepheline-sodalite syenite shows some evidence of being a ring-dike, however, for it is generally richest in feldspathoids in the middle and poorest in them along the margins. The impoverishment in feldspathoids along the margins might be considered to be a contact phenomenon, due to cooling effects at the contacts, which were about where they are now. The feldspathoid-rich middle of the ring would be younger than the edges, which agrees with the evidence that the feldspathoid-rich phases were last to solidify. The continuous nature of the variations within the nepheline-sodalite syenite seems to indicate differentiation in place. Under the ring-dike hypothesis, the differentiation would proceed from the feldspathoid-poor phases at the contacts to the feldspathoid-rich phases in the middle; the fire-tower syenite and other bodies within the ring would be separate later intrusions.

The main alternative explanation for the two outer rings is that they were successive plug-like intrusions and that the central portion of each was displaced by later intrusions. If this were true, the inner margin of the ring would be younger than the outside or the middle. This would mean that, in the nepheline-sodalite syenite, the outer feldspathoid-poor phase would be formed first; the differentiation in place would proceed to the formation of the feldspathoid-rich phase in the middle, and then it would go back to the formation of a feldspathoid-poor phase at the inner contact. The differentiation might or might not continue to the

[26] M. P. Billings: *Geology of the Littleton and Moosilauke quadrangles, New Hampshire*, N. H. State Planning and Development Comm. (1935).

M. P. Billings and C. R. Williams: *Geology of the Franconia quadrangle, New Hampshire*, N. H. State Planning and Development Comm. (1935).

R. W. Chapman: *Percy ring-dike complex*, Am. Jour. Sci., 5th ser., vol. 30 (1935) p. 401-431.

Louise Kingsley: *Cauldron-subsidence of the Ossipee Mountains*, Am. Jour. Sci., 5th ser., vol. 22 (1931) p. 139-168.

David Modell: *Ring-dike complex of the Belknap Mountains, New Hampshire*, Geol. Soc. Am., Bull., vol. 47 (1936) p. 1885-1932.

formation of the fire-tower syenite, but the three inner bodies would be later intrusions, as in the ring-dike explanation. This explanation—that the outer rings are due to successive plug-like intrusions—encounters the difficulty that it seems to involve a rather improbable reversal in a differentiation that seems to be continuous.

A further possible explanation of the concentric structure is that Red Hill is a type of zoned laccolith. The general sharpness of the contacts and the rather meager evidence that the contacts are almost vertical oppose such an origin. The reëntrant character of the contacts at some of the streams, as evidence of flat contacts, is discounted because of the many exceptions.

The relationships of the three interior bodies—the Watson Ledge quartz syenite, the Garland Peak syenite, and the interior fine granite—indicate rather definitely that they are plugs intruded into the fire-tower syenite.

MAGMATIC DIFFERENTIATION

GENERAL STATEMENT

Figure 4 shows graphically the chemical and mineralogical character of the rocks. It is important to notice that in the diagram of chemical variations the other constituents are not plotted against silica, as in the variation diagram, but that the rocks are arranged from left to right in the order of their age, from oldest to youngest, as well as from the outside of the mass to the interior.

The first change seems to have been toward less siliceous rock, as is represented by the change from the outer coarse syenite to the nepheline-sodalite syenite, which, in turn, changed from feldspathoid-poor phases to feldspathoid-rich rock. After the formation of the feldspathoid syenite the change was again toward more siliceous rocks, as is represented by the syenite, quartz syenite, and granite. Except within the feldspathoid syenite, these changes are manifested in distinctly different intrusions and must be due to differentiation before the magmas reached the position of the present rocks. The changes within the feldspathoid syenite, and possibly that from the feldspathoid syenite to the fire-tower syenite, were probably caused by differentiation in place. It is believed that the marginal feldspathoid-poor phases solidified first. That such is the order of chemical change is indicated by the fact that the parts of the rock richest in feldspathoids, especially sodalite, are the dikes and veinlets, which solidified last.

ORIGIN OF THE NEPHELINE-SODALITE SYENITE

The relationships of the Red Hill rocks agree in general with what was formerly known about nepheline syenites, and it is not expected that the facts presented here will go far toward solving the general problem

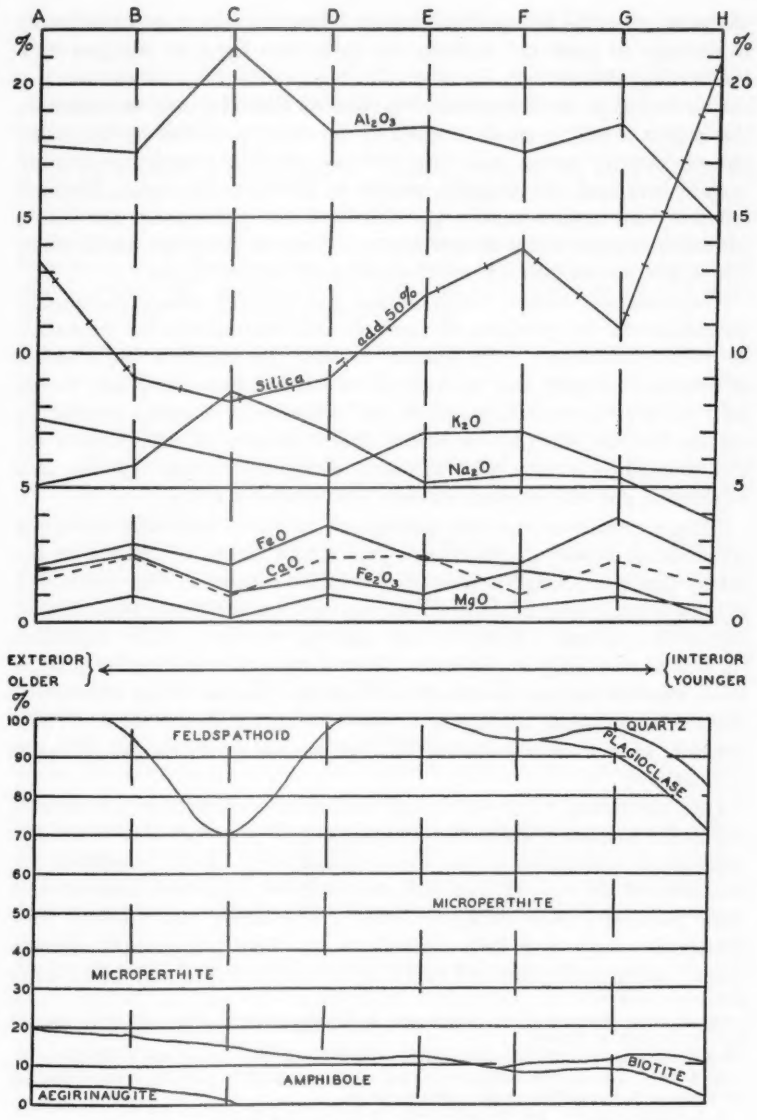


FIGURE 4.—*Chemical and mineralogical variations of Red Hill plutonic rocks*

of the origin of the feldspathoidal rocks. Nevertheless, it seems desirable to attempt to point out wherein the facts here agree or disagree with the leading theories.

The fact that the feldspathoid syenite at Red Hill and elsewhere in this region is only a small fraction of the rocks produced by this same igneous activity agrees well with previous ideas; the nepheline-sodalite syenite here and the analcite syenite at Pleasant Mountain, Maine,[27] together form approximately two-thirds of one per cent of the White Mountain magma series as now known. Most of the rocks produced by this larger igneous activity are of more nearly normal types.

The theories of Bowen, Daly, Gillson, and Smyth [28] assign considerable importance to the presence of much volatile material in the formation of feldspathoid rocks. The sodalite at Red Hill indicates the presence of chlorine, at least, and the veinlets of sodalite indicate a late, rather fluid phase; the cancrinite shows the presence of a small amount of carbon dioxide. Further evidences of the presence of mineralizers are the abundance of the rarer elements in sphene, zircon, apatite, and woehlerite, and the irregular streaky texture of the rock.

Gillson postulates that the passage of soda-rich solutions through a crystallizing cupola of granitic magma would enrich it in soda to the extent that a nepheline-bearing rock would be formed. The veinlets of sodalite furnish abundant proof that this rock was subject to the action of soda-rich solutions. However, the textural relations of the nepheline show it to be mainly a magmatic mineral, and indicate that the magma itself was rich in soda before crystallization. Gillson thinks the enrichment in soda might take place in part during the liquid stage. There seems to be no evidence at Red Hill for proving or disproving this part of the theory.

Daly and Shand [29] believe that assimilation of carbonate rock is important in the formation of feldspathoidal rock; they declare that there is a widespread association of the two types of rock. Daly recognizes the weakness of the case at Red Hill, however, but maintains that there is some possibility that carbonate rocks of the Montalban series of New Hampshire may have been assimilated by these intrusions.[30] Quartz diorite and granites surround Red Hill for several miles, and field studies

[27] W. F. Jenks: *Petrology of the alkaline stock at Pleasant Mountain, Maine,* Am. Jour. Sci., 5th ser., vol. 28 (1934) p. 321-340.

[28] N. L. Bowen: *The evolution of the igneous rocks,* Princeton Univ. Press (1928) p. 234-257.

R. A. Daly: *Genesis of the alkaline rocks,* Jour. Geol., vol. 26 (1918) p. 97-134; *Igneous rocks and the depths of the earth,* McGraw-Hill (1933) p. 483-544.

J. L. Gillson: *On the origin of alkaline rocks,* Jour. Geol., vol. 36 (1928) p. 471-474.

C. H. Smyth, Jr.: *The genesis of alkaline rocks,* Am. Philos. Soc., Pr., vol. 66 (1927) p. 535-580.

[29] S. J. Shand: *Limestone and the origin of feldspathoidal rocks,* Geol. Mag., vol. 67 (1930) p. 415-426.

[30] R. A. Daly: *Igneous rocks and the depths of the earth* (1933) p. 510-511.

impress one with the remoteness of the possibility of limestone assimilation.

From his study of the physical chemistry of silicate melts, Bowen has suggested several possible methods for the formation of feldspathoidal rocks. One method is:

"In the presence of water, there is a tendency towards the breakdown of the polysilicate molecules of the feldspars into the orthosilicate molecules of the micas, with setting free of SiO_2. . . . As the result of precipitation of the other molecules in the form of mica and quartz, there would be a concentration of the $NaAlSiO_4$ molecule in the residual liquor at a certain stage. The separation of the residual liquor, probably by a squeezing-out process, might then occur and thus an independent phonolitic liquid might originate." [31]

Considerable objection to this idea has been made, especially because of the fact that the residual liquor from granite magmas is invariably siliceous. This objection seems valid and is well illustrated by the interstitial character of the quartz in the quartz-bearing rocks of Red Hill. That is a general objection, however, and, if such a process does take place, it might explain the feldspathoidal magma that formed the nepheline-sodalite syenite.

Bowen describes, in considerable detail,[32] another method for the production of feldspathoidal rocks. A trachytic liquid is first produced from a basaltic magma by the prevention of the precipitation of an excess of olivine. The subsequent course of crystallization is controlled to some extent by the factors that cause the incongruent melting of orthoclase. Normally, leucite would form and then react with the more siliceous liquid to form orthoclase. If the liquid were removed before reaction took place, a feldspathoidal rock containing leucite would remain. Bowen makes a tetrahedral figure to show other courses of crystallization, the variations depending, in part, on the composition of the magma and, in part, on the amount of reaction during the crystallization. He points out certain conditions under which the crystallization proceeds to the formation of orthoclase, albite, and nepheline. The evidence that such has been the course of crystallization may be the presence of pseudo-leucite, but such evidence may be entirely lacking in certain instances. He states that "Such a liquid would form only nepheline, orthoclase, and albite without giving any suggestion of ever having been associated with leucite." [33] At Red Hill there is no leucite or pseudo-leucite to suggest such a process, but, as such evidence need not be present, it cannot be stated that the Red Hill rock was not formed in that manner. Here, again, the proof of the theory must depend on more general evidence.

[31] N. L. Bowen: *op. cit.*, p. 234.
[32] *Op. cit.*, chapter 12.
[33] *Op. cit.*, p. 255.

The fact that the feldspathoidal syenite in the rocks at Red Hill is not the end of the differentiation seems contrary to all these theories. Its intrusion is followed by the intrusion of syenite, quartz syenite, and granite. Presumably, the explanation is that there were later invasions of magma at a time when, or from a place where, differentiation was proceeding in the opposite direction—i.e., toward more siliceous rocks.

SUMMARY

The Winnipesaukee quartz diorite, which belongs to the New Hampshire magma series of probably late Devonian age, was intruded by the rocks of Red Hill, which belong to the White Mountain magma series of probably Carboniferous age. The White Mountain magma series rocks of Red Hill are divided into six petrographic types. The outer coarse syenite forms an irregular ring on the outside of the mass. Within it is an irregular ring of nepheline-sodalite syenite, within which the fire-tower syenite forms an oval-shaped body. The fire-tower syenite is cut by three small plug-like bodies—the Watson Ledge quartz syenite, the Garland Peak syenite, and the interior fine granite. Dikes of several types cut these Red Hill intrusions and the Winnipesaukee quartz diorite.

The order of the main intrusive bodies of Red Hill, from older to younger, is the same as their order of position from the outside to the interior. The outside ring of coarse syenite was apparently intruded as one body and shows no evidence of differentiation in place. The ring of nepheline-sodalite syenite seems to have been subject to some differentiation in place, the late liquid portions being enriched in feldspathoids. The fire-tower syenite may be gradational into the nepheline-sodalite syenite, but it is otherwise uniform and was probably intruded as one body with no differentiation in place. The three smaller bodies were later separate intrusions. The concentric arrangement of the outer coarse syenite and the nepheline-sodalite syenite suggests that they may be ring-dikes. There is no evidence aside from the shape that the outer coarse syenite is a ring-dike, and it might equally well be a plug with the center displaced by a later intrusion. The nepheline-sodalite syenite shows a decrease of feldspathoid content, both outward and inward, and that might be considered rather weak evidence for the ring-dike structure. The other intrusions appear to have been formed as plugs, with the later ones partially displacing the older ones.

Aside from the differentiation in place in the nepheline-sodalite syenite, the magmatic differentiation at Red Hill appears to have taken place at depth, before the intrusion to the present position of the rocks. The course of differentiation was from syenite to feldspathoid syenite, to syenite, to quartz syenite, to granite. The origin of the nepheline-

sodalite syenite is a special problem, and an attempt is made to point out wherein the facts at Red Hill agree or disagree with what is known about the feldspathoidal rocks in general and with the more important theories of the origin of the alkaline rocks. The facts—that the nepheline-sodalite syenite at Red Hill is a small part of the series of intrusions to which it belongs, that the other products of the igneous activity are more normal types of rock, and that there was volatile material associated with the feldspathoid magma—agree well with what is known about feldspathoid rocks. Gillson's theory that alkaline rocks may be due to the action of soda-rich solutions receives some support from the fact that the late liquid portions of the nepheline-sodalite were enriched in sodalite. Nepheline seems to be a magmatic mineral, rather than deuteric or hydrothermal, and it seems to have been formed without the action of soda-rich solutions. The limestone assimilation theory advocated by Daly and Shand seems improbable, because limestone is not known in this part of New Hampshire. The theories of Bowen are discussed, but the facts seem neither to prove nor to disprove his theories.

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LEATHERY SEA-WEEDS

Remains probably related to living Rhodochroaceae or red algae. From the Luta limestone, Big Blue series, Dickinson County, Kansas.

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DEPTH OF DEPOSITION OF THE BIG BLUE (LATE PALEOZOIC) SEDIMENTS IN KANSAS

BY MAXIM K. ELIAS

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HISTORY AND ACKNOWLEDGMENTS

This paper is based on observations, made chiefly during field research, and detailed mapping of the Big Blue series in the north-central part of Kansas in Marshall, Washington, Clay, and Dickinson counties in 1932 for the State Geological Survey of Kansas. Various points of cyclic analysis and problems of environments of Late Paleozoic sedimentation in the northern Mid-Continent have been discussed with Dr. R. C. Moore and Dr. N. D. Newell, of the University of Kansas. The manuscript has been read by Dr. Moore and Dr. W. H. Twenhofel, whose criticism and suggestions are gratefully acknowledged.

The application of the theory of cyclic sedimentation to the Big Blue series was reported to the Paleontological Society in 1933,[1] and its significance in stratigraphic classification of Late Paleozoic rocks in Kansas was discussed jointly with R. C. Moore at that time.[2] An attempt to estimate the depth of deposition of the Big Blue sediments in the light of cyclic analysis, and by comparison with the distribution of benthonic life in modern seas, was reported to the Society of Economic Paleontologists and Mineralogists at Wichita in 1935 and to the Paleontological Society at New York in 1935.[3]

Some evidence of cyclic repetition in the Big Blue series in northern Kansas, in which only lithologic changes were considered, has been independently discovered and discussed by Professor J. M. Jewett, of Wichita University.[4]

STRATIGRAPHIC POSITION AND CHARACTER OF THE BIG BLUE SERIES

The Big Blue series is the uppermost of the predominantly marine Late Paleozoic rocks of Kansas, above which are the largely continental red beds of the Permian Cimarron series (Fig. 1-E). The Big Blue corresponds to the Wolfcamp beds of Texas, to the Dunkard group of the Appalachian region, to the Autunian of France, the Lower Rotliegende of Germany, and the Upper Uralian of Russia.[5]

These Late Paleozoic rocks present an alternation of innumerable limestones, shales, sands, and coals. The separate formations and beds are famous for their lateral persistency. Many of the least conspicuous

[1] M. K. Elias: *Cycles of sedimentation in the Big Blue series of Kansas* (abstract), Geol. Soc. Am., Pr. 1933 (1934) p. 366.

[2] R. C. Moore and M. K. Elias: *Sedimentation cycles as a guide to stratigraphic classification of the Kansas Lower Permian* (abstract), Geol. Soc. Am., Pr. 1933 (1934) p. 100.

[3] M. K. Elias: *Depth of deposition of the Big Blue Sediments* (abstract), Geol. Soc. Am., Pr. 1935 (1936) p. 375.

[4] J. M. Jewett: *Evidence of cyclic sedimentation in Kansas during the Permian period*, Kans. Acad. Sci., Tr., vol. 36 (1933) p. 137-140.

[5] The Big Blue series is classed as Lower Permian, but it is recognized that this age assignment is dependent on definition of the basal Permian boundary in Russia. If the base of the type Russian Permian is placed at the bottom of the Artinsk beds, then most of the Big Blue series should be classed as Upper Carboniferous.

limestones have been traced across Kansas and adjacent parts of Nebraska and Oklahoma, and some zones, only a few inches thick, marked by distinctive lithology and fossil content, occupy the same relative position within the limestone throughout their outcrop. An equal persistency of succession, modified to some extent by gradual changes in prominence of calcareous sediments, which are apparently due to deposition in slightly deeper portions of the epeiric sea, has been discovered in deep wells drilled in western Kansas, where the Paleozoic rocks are covered by Cretaceous and Tertiary beds. The alternation of marine sediments, mainly limestones and calcareous shales, with non-marine sediment, sands, red shales, and coals, is explained as a result of repeated invasions and retreats of oceanic waters.

The regular, predominantly limestone-and-shale, alternation is broken by moderately strong disconformities, which signify erosional intervals that were followed by deposition of prominent sands and sandy shales in local erosion channels. The youngest of the locally recognized Late Paleozoic major unconformities [6] marks the beginning of the Big Blue series, which differs from the preceding, Late Pennsylvanian, series by (1) still greater persistency and uniformity of its limestones and shales, (2) the nearly total disappearance of sands and conglomerates, (3) the disappearance of coals (except a few thin, locally developed beds), (4) the prominent development of red and green shales, and (5) the introduction of some gypsum and salt, especially in the upper part of the series.

Clearly, after the last slight rejuvenation of topography at the beginning of Big Blue time, which resulted in some deposition of sands at and near the base of the series, the subsequent invasions and retreats of the sea resulted in deposition of only silts and clays intercalated between the marine limestones. Undoubtedly, the sea waters made still more level and featureless the platform, which, even before Big Blue time, was an almost perfectly flat plain.

The leveling process was accompanied by simplification of the marine life. The diversified fauna of the preceding Pennsylvanian epochs disappeared rapidly. For example, of 40 to 45 species of brachiopods known from the lower part (Foraker limestone and below) of the Big Blue beds, not more than 10 survive above the Fort Riley limestone of the middle of the series. A considerable decrease in number of species is also noticeable in other groups of marine invertebrates. At the same time, the few surviving species become extremely numerous, at places excluding other organic remains. In the last invasions of the Big Blue sea, some marine invertebrates disappear completely in the following order:

[6] R. C. Moore and R. G. Moss: *Permian-Pennsylvanian boundary in the northern Mid-Continent area* (abstract), Geol. Soc. Am., Pr. 1933 (1934) p. 100.

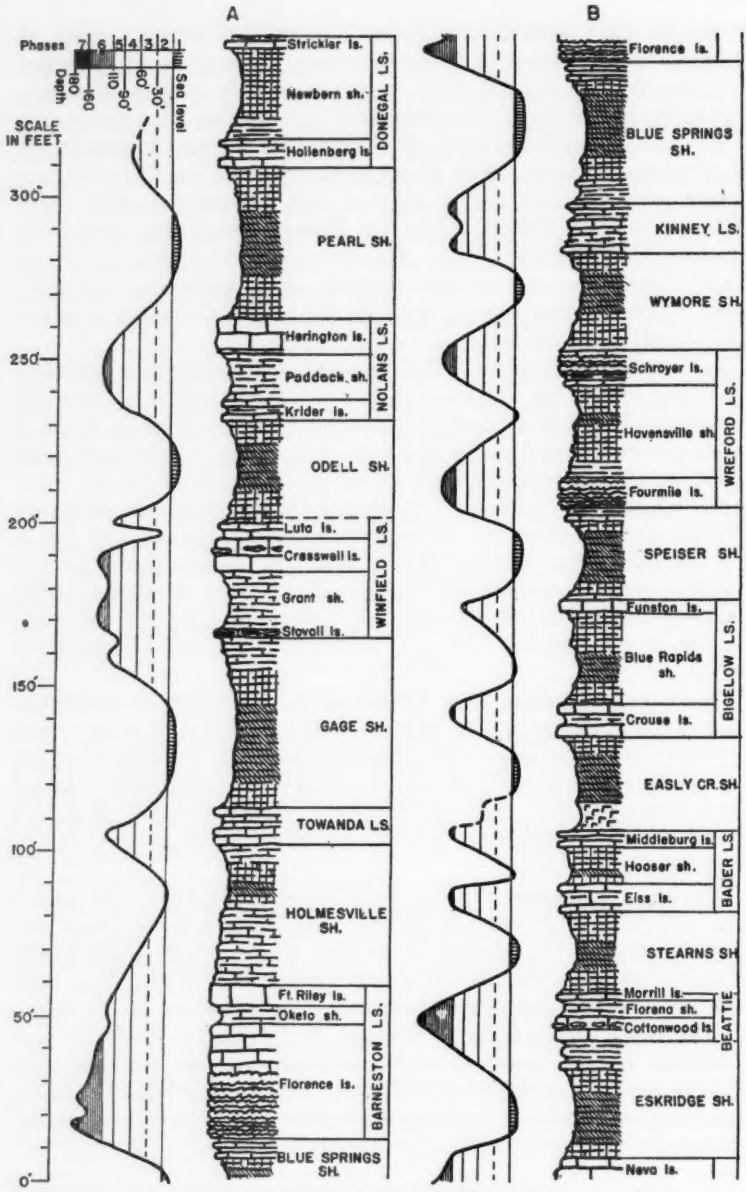

FIGURE 1.—*Cycles in the Big Blue series*

A, B, and C.—Composite geologic section of the part of the Big Blue series in northern Kansas, interpreted in terms of cyclic sedimentation and depth of deposition.

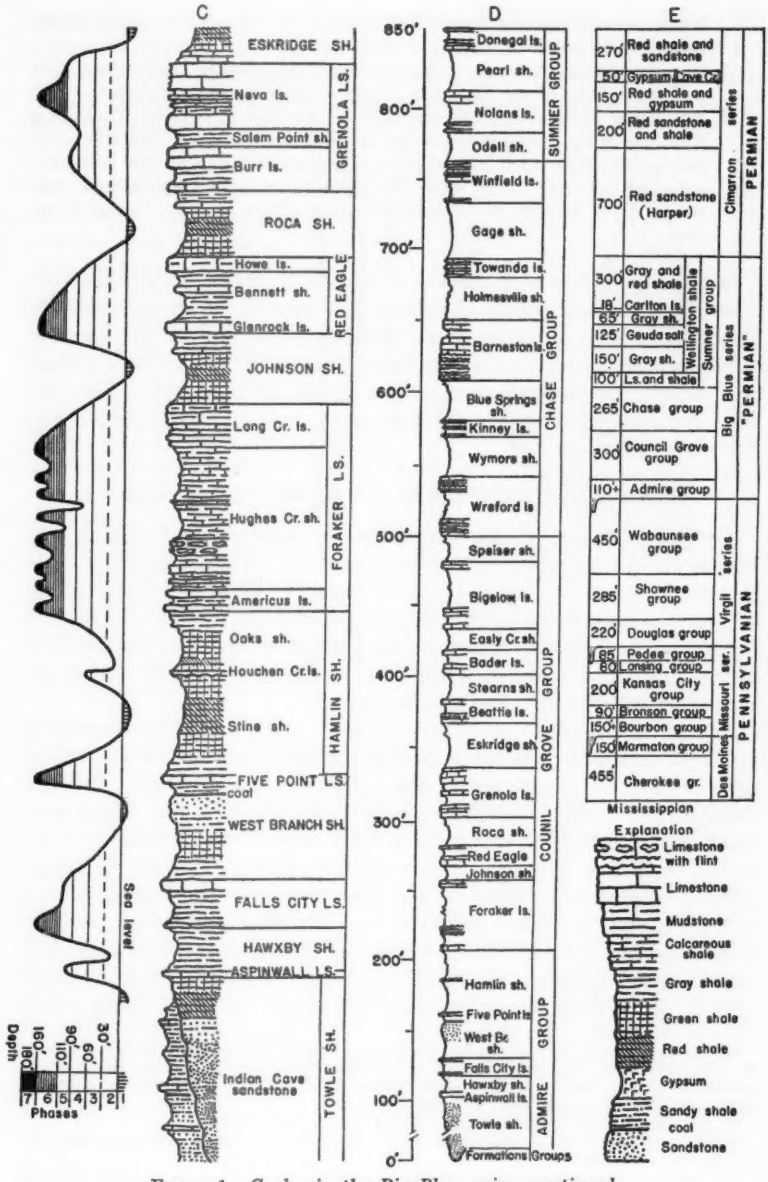

FIGURE 1.—*Cycles in the Big Blue series—continued*

D.—Key section for A, B, and C, showing formations and groups of the Big Blue series.
E.—Key section, showing position of the Big Blue series among the Late Paleozoic rocks of Kansas.

1. Fusulinids are observed for the last time in the Florence limestone of the Barneston cyclothem.
2. Brachiopods and bryozoans make their last appearance in the Paddock shale and at the base of the Herington limestone of the Nolans cyclothem.
3. The larger mollusks appear practically for the last time in the Hollenberg limestone of the Donegal cyclothem, in which they are rare. Small *Myalina* and a few other small pelecypods and gastropods are observed in a thin unnamed limestone in the lower Wellington shale and in the Carlton limestone. A few pelecypods and gastropods are known from the Cimarron red beds.

In the light of the next chapter discussion, it becomes clear that the order in which these groups of animals disappear in the stratigraphically highest cyclothems of the Big Blue indicates general decrease in extension or gradual shallowing of the last marine invasions. Later in Big Blue time, lagoons became numerous, in which rock salt and gypsum accumulated, followed by the prolonged continental stage of later Permian and Early Mesozoic time.

CYCLIC SEDIMENTATION OF THE BIG BLUE SERIES

The cyclic nature of the succession of sediments and faunas was reported to the Paleontological Society in 1933.[7] The sedimentary cycle involves both marine and continental deposits. They are intermediate between the great cycles of the geologic periods [8] and the minute seasonal rhythm of varved clays. They are comparable in magnitude to the sedimentary cycles observed in Kansas and elsewhere in beds of Dinantian, Pennsylvanian, Jurassic, and Eocene age.

The guiding lithologic units that determine the limits of the succeeding cycles of deposition are the persistent unfossiliferous red shales, which seem to have been developed in times of prolonged emergence. Between these are green, gray, and brown marine shales and light-gray limestones, which are, generally speaking, very fossiliferous. As indicated by the fossils, these beds were deposited in shallow waters. The orderly occurrence of mollusks, brachiopods, and fusulinids was found most helpful in establishing the cyclic character of sedimentation. In successively higher levels of the fossiliferous strata, the most common marine animals appear in the following order: (1) corneous brachiopods,[9] (2) mollusks (chiefly pelecypods, less plentifully gastropods, and still more rarely

[7] M. K. Elias: *Cycles of sedimentation in the Big Blue series of Kansas* (abstract), Geol. Soc. Am., Pr. 1933 (1934) p. 366. The cyclic succession of some lithologic units in the Big Blue series has been noticed also by J. M. Jewett: *Evidence of cyclic sedimentation in Kansas during the Permian period*, Kans. Acad. Sci., Tr., vol. 36 (1933) p. 137-140.

[8] J. W. Dawson: *Acadian Geology* (Geologic cycles) 2d ed. (1868) p. 135-138.

J. S. Newberry: *Circles of deposition in American sedimentary rocks*, Am. Assoc. Adv. Sci., Pr., vol. 22 (1874) p. 185-196.

[9] This phase of the progressive hemicycle has been actually observed only in some Pennsylvanian cycles below the Big Blue series, but it was observed in some regressive hemicycles of the latter series.

nautiloids), (3) calcareous brachiopods, and (4) fusulinids. Above the zone of fusulinids, these marine forms appear in exactly opposite order.

Although the general order of appearance of these faunal groups is always the same, they only rarely make clean-cut faunal zones, except the fusulinids, which generally are alone. Ordinarily, even as in modern seas, the faunal groups overlap each other to greater or lesser extent. It is noticed that the stoutest or most greatly inflated among the observed pelecypods[10] (*Allorisma* and *Pinna*, Fig. 2) seem to prefer the society of calcareous brachiopods and of fusulinids, whereas the flat-shelled pelecypods alone (*Aviculopecten, Pleurophorus*) were found in a few beds with the corneous brachiopods (*Lingula, Orbiculoidea*). Among the calcareous brachiopods, *Juresania* is most constantly associated with molluscan faunas.

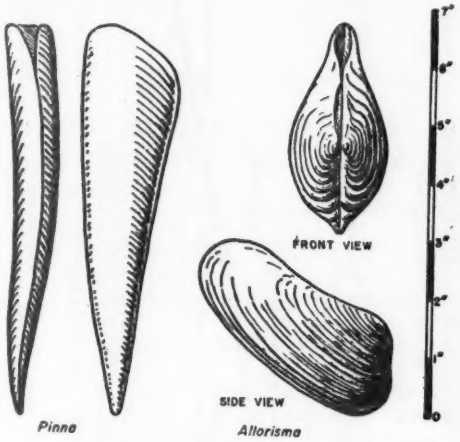

FIGURE 2.—*Burrowing clams*

Most common burrowing marine clams from the Late Paleozoic rocks of Kansas, shown in their natural position, which they acquired when they buried themselves in originally unconsolidated marine sediments of the Late Paleozoic.

In addition to these fossils, which are most useful in establishing the cyclic succession of the faunal zones, less common ones have also a fairly definite position within the cycles.

The few corals, which seem to belong to *Lophophyllum*, are found exclusively in the brachiopod and mixed-fauna phases. The much more common Bryozoa, mostly represented by fenestrate forms, *Rhombopora, Meekopora*, and others, are found in brachiopod(6) and mixed fauna(5) phases and also extend into the adjoining part of the molluscan(4) phase. The gastropods are found in the molluscan(4) and mixed fauna(5) phases, where also belong the few collected nautiloids and ammonoids. Ostracodes are numerous in the molluscan phases(4) of some cyclothems, but they may be present also in the deeper water phases. Rare fish remains (chiefly scales) are observed in the molluscan(4) and mixed(5) phases.

[10] These were undoubtedly burrowing forms.

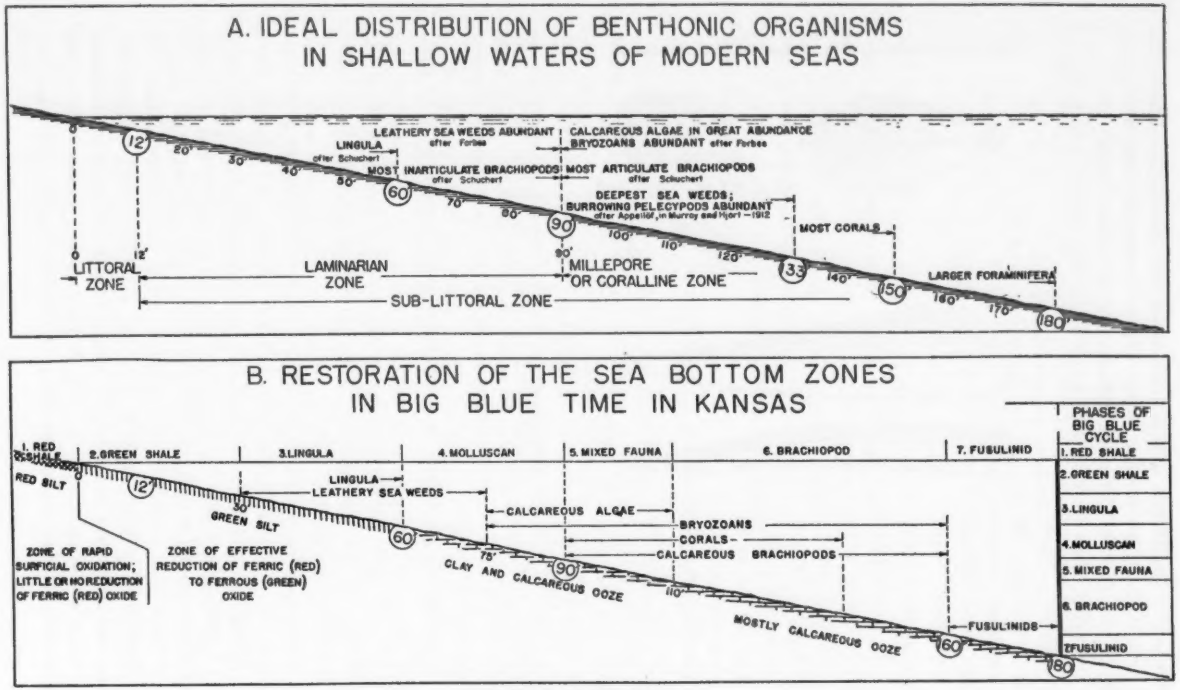

FIGURE 3.—*Sea-bottom zones in modern and in Big Blue seas*

A.—Ideal distribution of benthonic organisms in shallow waters of modern seas.
B.—Restoration of the sea bottom zones in Big Blue time in Kansas.

The few remains of terrestrial plants have no particular environmental significance, and they are naturally found in greatest quantities in the deposits that were formed nearest to the shore—that is, in the molluscan(4) phase, *Lingula*(3) phase, and the green shale beds(2). Much

TABLE 1.—*Idealized Big Blue cycle of deposition in north-central Kansas*

	No.	Phases established chiefly on paleontologic evidence	Corresponding typical lithology
Regressive hemicycle	1.	Red shale	Clayey to fine sandy shale, rarely consolidated.
	2r.	Green shale	
	3r.	Lingula phase	Sandy, often varved (?), rarely clayey shale.
	4r.	Molluscan phase	Clayey shale, mudstone to bedded limestone.
	5r.	Mixed phase	Massive mudstone, shaly limestone.
	6r.	Brachiopod phase	Limestone, flint, calcareous shale.
	7.	Fusulinid phase	
Progressive hemicycle	6p.	Brachiopod phase	
	5p.	Mixed phase	Massive mudstone, shaly limestone.
	4p.	Molluscan phase	Clayey shale, mudstone to bedded limestone.
	3p.	Lingula phase	Sandy, often varved (?), rarely clayey shale.
	2p	Green shale	Clayey to fine sandy shale, rarely consolidated.
	1.	Red shale	

more important ecologically are marine algae. These include (1) the impressions and pseudomorphic replacements of thalloid-like branchlets, which apparently belong to Rhodochroaceae or red algae (Pl. 1), and (2) the massive calcareous encrustations and branching colonies, which were described from the local Pennsylvanian under the names *Cryptozoon, Osagia, Ottonosia,* and *Somphospongia* (which is not a sponge). The thalloid-like impressions are found exclusively in green shales (2) and in impure limestones and dolomites of the molluscan phase (4), but the calcareous encrusting algae may be collected from the molluscan(4) and mixed fauna(5) phases. In the Pennsylvanian cycles, they are also in the brachiopod(6) and rarely in fusulinid(7) phases.

No single cycle of the Big Blue rocks shows all phases of the ideal cycle, but the missed phases in one cycle appear in proper position in neighboring cycles above and below. The nearest approach to the ideal is reached in the Beattie and Barneston cycles. Excepting phase 3p, these cycles are practically complete.

The lithologic expression of the faunal phases is somewhat variable.

Some phases of different cycles, however, are expressed by characteristic and persistent lithologic units. For instance, the progressive mixed fauna phases (5p) of the Wreford and Florence cycles form persistent ledges of mudstone, separated by calcareous brachiopod-bearing shale (6p) from the main solid limestones. Although a general increase in content of calcium carbonate is found in the strata in passing from the red shale (1) to the fusulinid (7) phase, the beds of thickest and hardest limestone do not everywhere correspond exactly to the fusulinid (7) and brachiopod (6) phases of a cycle. In some cycles, especially toward the top of the Big Blue series, the mixed (5) and the pelecypod (4) phases are found in the thickest limestones of the cycle, whereas the brachiopod (6) phase is expressed partly or entirely in the form of calcareous shale. Although flint nodules and bands appear generally within phases 6 and 7, some thin and local bands of flint are observed rarely in phases 4 and 5.

ZONAL DISTRIBUTION OF BENTHONIC LIFE IN SHALLOW DEPTHS OF MODERN SEAS

GENERAL STATEMENT

The distribution of organisms on the bottom of modern seas is greatly affected not only by the depth but also by various other factors, such as temperature, degree of clearness and salinity of the water, presence of currents, and character of the bottom. Some generalizations in regard to the relative position of benthonic zones, largely controlled by their depths, have been reached. These are summarized and the main conclusions are presented in graphic form (Fig. 3-A).

OBSERVATIONS BY FORBES

The extensive study in the Aegean sea, and around the coasts of Great Britain, made by Forbes [11] is still one of the main sources of information on the distribution of benthonic organisms, and his principal shallow-bottom zones are generally accepted.

In 1844, Forbes [12] defined the littoral zone (first region) as the zone of tides, extending down to a depth of 2 fathoms, in which *Pinna squamosa* is abundant. The deeper portions of the sea were divided into regions as follows: Second region, depths ranging from 2 to 10 fathoms, burrowing conchifera abundant; third region, depths ranging from 10 to 20 fathoms, corallines more plentiful.

[11] Edward Forbes: *Report on the Mollusks and Radiata of the Aegean Sea, and on their distribution as bearing on geology*, Brit. Assoc. Adv. Sci., 13th Rept. (1844) p. 130-193; *On the connection between the distribution of the existing fauna and flora of the British Isles, and the geological changes which have affected their area . . .* , Geol. Surv. Great Britain, Mem., vol. 1 (1846) p. 336-432; *Report on the investigations of British marine zoology by means of the dredge*, pt. 1, Brit. Assoc. Adv. Sci., 20th Rept. (1851) p. 192-263.

[12] Edward Forbes: *Report on the Mollusks and Radiata of the Aegean Sea, and on their distribution as bearing on geology*, Brit. Assoc. Adv. Sci., 13th Rept. (1844) p. 154-161.

Subsequently, Forbes [13] defined the zones included between depths of 15 and 20 fathoms as the region of *Nullipora* and remarks that below 20 fathoms "no decided algae were met with." This statement, however, refers primarily to leathery sea-weeds (= decided algae), because, at that time most calcareous algae were believed to be related to corals. He introduced the terms "Laminarian region" for low-water mark, down to 15 fathoms, and "Coralline region" for the interval between 15 and 40 fathoms. The latter region is subdivided into an upper part, from 15 to 25 fathoms, and middle and lower parts, from 25 to 40 fathoms.[14] Forbes speaks in this paper also of the shallow waters below the zone of tides as the "sublittoral" part of the sea bottom.

Summarizing, the following scheme, modified after Forbes,[15] is derived. The slope of shallow seas is divided into three principal zones: (1) Littoral zone, between highest and lowest tide marks; (2) laminarian zone, from low-tide mark to a depth of 15 fathoms, characterized by leathery sea-weeds, which afford shelter to many mollusks; (3) coralline zone, from 15 to about 40 fathoms, characterized by abundance of calcareous algae, leathery sea-weeds being only sparingly present in the shallow end of this zone. According to Appellöf [16] and Foslie,[17] however, lime-secreting algae are abundant not only in the coralline zone, but also in the laminarian zone and in the zone of tides. It is the *abundance* of leathery sea-weeds in the laminarian zone, therefore, and their disappearance at greater depths, that defines the limit between the laminarian and the coralline zones. The most typical lime-secreting plants of the coralline zone are the red algae, encrusting *Lithothamnium*, and branching *Corallina*. Bryozoa are abundant in this zone.

LITTORAL AND SUB-LITTORAL ZONES

Some modern writers use the terms "littoral" and "sublittoral" in a different sense than that originally defined by Forbes. For instance, Grabau [18] designated as littoral "all that part of the sea above the deep-sea portion, *i.e.*, approximately above the hundred-fathom line"; the original littoral zone of Forbes, he calls "littoral in restricted sense" or "shore zone." Peterson [19] uses the term littoral in the sense of Grabau. On the

[13] Edward Forbes: *Report on the investigation of British marine zoology by means of the dredge*, pt. 1, Brit. Assoc. Adv. Sci., 20th Rept. (1851) p. 246, 247.

[14] *Op. cit.*, p. 252.

[15] Edward Forbes: *On the connection between the distribution of the existing fauna and flora of the British Isles and the geological changes which have affected their area . . .*, Geol. Surv. Great Britain, Mem., vol. 1 (1846) p. 375.

[16] A. Appellöf: *Invertebrate bottom fauna* in J. Murray and Johan Hjort: *Depths of the ocean* (1912) p. 459-526.

[17] M. Foslie: *Norwegian forms of Lithothamnion* (1894) Trondhjem, Norway; *Lithothamnia of the Maldives and Laccadives*, in Stanley Gardiner: *Fauna and geography of the Maldive and Laccadive Archipelagoes*, vol. 1 (1903) p. 460-471. Cambridge Univ. Press.

[18] A. W. Grabau: *Principles of stratigraphy* (1913) p. 470.

[19] C. G. J. Peterson: *On the animal communities of the sea-bottom in the Skagerak, the Christiania Fjord and the Danish waters*, Danish Biol. Stat., Copenhagen, Rept. XXIII (1915).

other hand, Appellöf [20] applies "littoral" to the portion of the sea bottom from shore line to a depth of 30 to 40 meters, and Neaversen [21] uses this term for the zone between the shore and a depth of 15 to 20 fathoms. These authors apply the term "sub-littoral" to the region below littoral down to 150 meters (Appellöf) or to 80 fathoms (Neaversen).

In view of the confusion arising from these varying definitions, Allee [22] suggests that "littoral" be used only in the original sense of Forbes. This conforms with a general tendency of modern science to follow rules of priority in use of terms. As the lower limit of the "sub-littoral" zone was not defined by Forbes, it is permissible to designate this according to Appellöf—that is, a depth of 30 to 40 meters, which is "almost as far down as there are sea-weeds." [23] The upper limit of the "sub-littoral" zone, however, remains as indicated by Forbes—that is, at low tide (12 feet).

OBSERVATIONS BY APPELLÖF

Important additional data on the shallow zones as observed in the Norwegian sea and adjacent part of the Atlantic are given by Appellöf. A zone extending downward to a depth of 30 or 40 meters is characterized by "periodic changes in temperature and salinity, strong light, and a great variety in the materials at the bottom, such as loose stones, solid rock, sand with or without coarse or fine fragments of different kinds of shells, mud and 'mixed mud'—that is to say, sand, mud, and stones are mixed together. Here we find the whole vegetation collected, consisting of fucoids, green and red algae, *Laminaria*, and *Zostera* [eelgrass], all of which, as a rule, form big independent communities that are very often arranged in belts." [24] The next deeper zone, extending down to 150 meters is marked by absence of vegetation, greater uniformity in the nature of bottom deposits, higher and more constant salinity and less pronounced differences in temperature.[25] Below this is the "continental deep-sea zone, ranging from 150 to 1,000 meters or more."

The following typical organisms were observed by Appellöf in the zone of tides, only those belonging to classes that are found preserved as fossils being here mentioned. (1) On rocky bottom: Barnacles (*Balanus balanoides*), mussels (*Mytilus edulus*), gastropods (cap-shaped limpet, *Patella vulgata;* periwinkles, *Littorina littorea, L. rudis;* purple snail, *Purpula lapillis*). Except the limpets, these forms live also on the algae. Algae, however, and *Fucus* in particular usually have their special fauna

[20] A. Appellöf: *op. cit.*, p. 459.
[21] Ernest Neaversen: *Stratigraphical paleontology* (1928) p. 87. Macmillan and Co., London.
[22] W. C. Allee: *Studies in marine ecology*, Biol. Bull., vol. 44 (1923) p. 169.
[23] A. Appellöf: *op. cit.*, p. 459. The sea-weeds, however, extend downward to about 200 feet.
[24] *Ibid.*
[25] *Op. cit.*, p. 459-460.

consisting chiefly of attached forms. Bryozoa (*Alcyonidium hirsutum, Flustrella hispida, Bowerbankia imbricata*) are common and fucoids are often densely thronged by small white spiral-shaped tube-worms (*Spirorbis*). (2) On sandy bottoms: Burrowing forms predominate. Pelecypods (sandgaper, *Mya arenaria;* cockle, *Cardium edule*) are common.

Appellöf does not subdivide the belt between low-tide mark and 40 meters depth. He mentions the sea-weeds, *Laminaria hyperborea, L. digitata* and *L. saccharina,* growth of which begins immediately below the fucoids of the zone of tides. Although *Laminaria* grows in exposed situations where there are waves and strong currents, there is a hard bottom that serves as a place of attachment. The eelgrass (*Zostera marina*) grows at the same depths on soft muddy bottoms of sheltered pools and estuaries. On blades of Laminaria are found the encrusting bryozoan *Membranipora membranacea,* calcareous sponges, and a few siliceous sponges. The importance of the 40-meter mark is emphasized, because, among the forms characteristic of the "littoral" zone, "there are very few that do not occur in all its depth"; these few, such as *Mya arenaria* and *Cardium edule,* are restricted to the "tidal area." [26]

Appellöf notes that "the limits between a littoral and non-littoral zone seem to be less clearly defined in the Arctic than in the Boreal region. The reason for this is obvious enough if we remember that temperature largely controls distribution." [27]

INFLUENCE OF COMPOSITION OF SEA-BOTTOM

The nature of the sea-bottom is important in the distribution of benthonic animals, and, in some cases, this overbalances depth. For instance, Herdman [28] states that one can find within a single zoological province a similar fauna on muddy bottoms in depths of from 10 to 50 fathoms. Sumner, [29] likewise, states that the character of the bottom, considered chiefly in relation to texture, is "foremost among the conditions determining the distribution of the bottom dwelling organisms." It is clear, however, that, wherever there is little difference in the physical character of the sediments, depth is the main control in distribution of the bottom-dwelling organisms that arrange themselves in belts more or less parallel to the shore line.

OBSERVATIONS BY PETERSON

Peterson's detailed studies in the Danish waters are particularly instructive. He found that certain species of pelecypods, echinoids, and

[26] *Op. cit.*, p. 479.
[27] *Op. cit.*, p. 526.
[28] W. A. Herdman: *Marine zoology of the Irish sea,* Brit. Assoc. Adv. Sci., Rept. (1894) p. 318-334.
[29] F. B. Sumner: *An intensive study of the fauna and flora of restricted area of sea bottom,* U. S. Bur. Fish., Bull., vol. 28 (1908) p. 1229.

starfishes are narrowly restricted to particular depths. His classification follows:

(1) Depth about 5 meters, *Macoma balthica* (pelecypod)
(2) Depth about 10 meters, *Venus gallica, V. ovata* (pelecypods)
(3) Depth about 15 meters, *Echinocardium, Venus* (pelecypods)
(4) Depth about 20 to 30 meters, *Echinocardium* (pelecypod), *Amphiura filiformis* (starfish)
(5) Depth about 40 to 80 meters, *Brissopsis lyrifera* (echinoid), *Amphiura chiajei* (starfish)
(6) Depth about 100 to 150 meters, *Brissopsis lyrifera* (echinoid), *Ophyoglypha sarsii* (starfish)
(7) Depth down to 670 meters, *Amphilepis norvegica* (starfish), *Pecten vitrens* (pelecypod).

The first four zones make up the Laminarian zone of Forbes. Peterson's fifth zone approximately corresponds to the Coralline zone of Forbes. Zones 5 and 6 comprise the sub-littoral zone of Appellöf.

OBSERVATIONS BY FISHER

Fisher [30] lists gastropods that are restricted in bathymetric range.

(1) Littoral zone: *Littorina, Hydrobia, Assiminea, Rissoa, Truncatella, Cerithium, Natica, Pyramidella, Nassa, Purpura, Murex, Conus.*

(2) Laminarian zone (from low tide to depth of 90 feet): *Phasianella, Xenophora, Triforis, Rissoa, Aclis, Daphnella, Lacuna, Terebellum, Pterocera, Marginella, Mitra, Nassa, Phos, Drillia, Pleurotoma.* According to Woodward,[31] the species of these genera are mostly phytophagous, feeding on algae, but here are also found carnivorous species of *Buccinum, Nassa,* and *Natica.*

(3) Zone from 90 to 300 feet: mainly carnivores of the genera *Bela, Buccinum, Cassis, Cassidaria, Chenopus, Eulima, Fossarus, Fusus, Nassa, Natica, Pleurotoma, Trichotropis, Tritonium, Trophon,* and *Velutina.* According to Woodward,[32] the vegetable-eaters are represented by *Fissurella, Emarginula, Pileopsis, Eulima,* and *Chemnitzia.*

The conclusions derived from the extensive observations of Forbes, Appellöf, Peterson, and others, indicate that "one of the most important controlling factors is depth, and we find, running roughly parallel to the coasts, a series of bathymetrical zones, each characterized by a community, or by a series of communities determined by other controlling factors such as mineral composition of the sea-bottom." [33]

An example of differentiation of communities determined by character

[30] Paul Fisher: *Manual de Conchyliologie* (1887). Paris.
[31] S. P. Woodward: *Manual of the Mollusca,* 4th ed. (1880) or reprint (1890) p .151. Lockwood and Son, London.
[32] *Op. cit.,* p. 152.
[33] A. M. Davies: *Sequence of Tertiary faunas,* in *Tertiary faunas,* vol. 2 (1934) p. 53-55 [Cycles of sedimentation]. Thomas Murby and Co., London.

of sea bottom within a single bathymetrical zone has been given by Forbes for his littoral zone.

"Throughout Europe, where it consists of *rock*, it is characterized zoologically by species of *Littorina*, botanically by *Corallina;* where *sandy*, by the presence of certain species of *Cardium, Tellina* and *Solen;* where *gravelly* by *Mytilus;* where *muddy* by *Latraria* and *Pullastra*." [34]

BRACHIOPODS

In 1911, Schuchert [35] concluded that "between low-water and above 90 feet of depth the great majority of inarticulate or corneous brachiopods live, or 21 species of a total of 29 (*Lingula*, 11; *Glottidia*, 4; *Discina*, 1; *Discinisca*, 4; and *Crania*, 1). Of the articulate brachiopods, 23 out of the 129 live in these shallow waters." The remaining seven species of living inarticulate (corneous) brachiopods (*Discinisca*, 1; *Crania*, 6) appear from 90 feet down to 600 feet. Schuchert adds that the most conspicuous of the "shallow-water forms are of *Lingula* and *Discina*, genera that are restricted" to the zone "from the strand-line to a depth of probably not much more than 60 feet." [36] This places these living shells within the Laminaria zone of Forbes. The position of this zone on chart (Fig. 3A) corresponds closely to that of the *Lingula* phase in chart (Fig. 3B).

It is interesting to add that "many of the species of lingulids occur in bays and estuaries, indicating that they prefer a habitat more or less freshened by land waters." [37]

Schuchert points out that "of the 129 articulate species about 19 percent (25 species) live in less than 90 feet of water. Their real habitat, however, is in the deeper water between 90 and 600 feet, where nearly 46 percent (59 species) live. Down to 600 feet occur 84 articulate and 28 inarticulate forms, or, in other words, more than 70 percent of brachiopods are at home in these shallower waters. We may, therefore, conclude that the greatest abundance of living brachiopods is in the stormless waters between 90 and about 500 feet depth." [38]

The 90-foot mark, which Schuchert selects as the important lower boundary for the zone of abundant inarticulates, corresponds satisfactorily to the boundary on the restored Big Blue sea floor between the zone of pelecypods, containing some corneous brachiopods, and the next underlying zone, in which calcareous brachiopods begin to predominate.

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[34] Edward Forbes: *On the connection between the distribution of the existing fauna and flora of the British Isles, and the geological changes which have affected their area . . .*, Geol. Surv. Great Britain, Mem., vol. 1 (1846) p. 371.

[35] Charles Schuchert: *Paleogeographic and geologic significance of recent Brachiopoda*, Geol. Soc. Am., Bull., vol. 22 (1911) p. 260.

[36] *Op. cit.*, p. 262.

[37] *Ibid.*

[38] *Op. cit.*, p. 265.

CORALS

The reef-forming corals do not flourish below 25 fathoms,[39] as estimated originally by Darwin and confirmed by extensive recent investigations. Few reef-builders are found at greater depths (*Dendrophyllia* to 50 fathoms) in tropical and temperate waters, together with a few non-colonial corals. The most common solitary corals (*Balanophyllum, Coryophyllia*) in northern European seas are found in the zone of low tides and are widely distributed in shallow waters of the Mediterranean (*Caryophyllia*) and Indian Ocean (*Paracyathus*).[40]

FORAMINIFERA

The small planktonic Foraminifera are known to accumulate at depths of 3,000 to 5,000 meters, but the bathymetric position of the larger Foraminifera is of interest in considering probable depths indicated by fusulinids. According to Galloway,[41] "the fusulinids lived in shallow water and must have been benthonic, for such large heavy tests could scarcely have floated. Beede has expressed the opinion that *Schwagerina* may have been pelagic, but its wide geographic range could be explained by its dispersal in the nepionic stage." Thus, it seems probable that the fusulinids lived at depths comparable to those inhabited by modern large benthonic Foraminifera. The modern larger Foraminifera of the families Alveolinellidae, Camerinidae, and others, are almost exclusively tropical, in waters less than 30 fathoms deep.[42]

BRYOZOA

The relationship of certain types of bryozoan zoaria to habitat is discussed by Stach,[43] on the basis of observations, chiefly along the coasts of Australia. He distinguishes nine principal zoarial types for living and Cenozoic cheilostome bryozoans. Most of these can be recognized also among Paleozoic Gymnolaemata. The encrusting forms of *Fistulipora, Tabulipora,* and other "stony" bryozoans, for instance, belong to Stach's *membraniporiform* type of zoarium. *Meekopora* and other bilaminate forms are eschariform; *Fenestrellina* (*"Fenestella"* of authors) and *Polypora* are reteporiform; and *Rhombopora* and other rod-shaped rigid branching types with solid core possess vinculariform zoaria. Among these four types only the encrusting membraniporiform zoaria are found in both littoral and sub-littoral zones. These extend also "to deeper waters but are there numerically unimportant."[44] The bilaminate eschariform zoa-

[39] T. W. Vaughan: *Physical conditions under which Paleozoic coral reefs were formed,* Geol. Soc. Am., Bull., vol. 22 (1911) p. 248.

[40] S. J. Hickson: *Introduction to the study of recent corals,* Univ. Manchester Publ., Biol. ser., no. 4 (1924) p. 37-38.

[41] J. J. Galloway: *Manual of Foraminifera* (1933) p. 391. The Principia Press, Indiana.

[42] J. A. Cushman: *Foraminifera* (1928, *also* 1933) p. 39.

[43] Leo W. Stach: *Correlation of zoarial form with habitat,* Jour. Geol., vol. 44 (1936) p. 60.

[44] *Op. cit.,* p. 61.

rium of modern Bryozoa is "adapted for life in sublittoral zones at depths of at least 10 fathoms" (60 feet). "It may extend to deeper water, but not to the littoral zone"—that apparently means above 60 feet. The reteporiform or fenestrate type of zoarium "is adapted for life in regions where wave action and currents are strong" and "is most prolific in sublittoral regions." The branching vinculariform types "are adapted for life in deep or sheltered waters where wave action is absent and currents scarcely active." Only the fenestrate types of Bryozoa, *Fenestrellina* (*Fenestella* of authors) and *Polypora*, have been observed by the writer in the molluscan (4) and mixed (5) phases of the Big Blue cycles, but all four indicated types of zoaria are represented in the brachiopod phase. These observations provide further support for the conclusion that the phase of calcareous brachiopods belongs to bottoms below 60 feet.

MOLLUSKS

The position of pelecypods and other mollusks in the Big Blue cycle is fairly conformable to that in modern seas. According to Forbes,[45] the mollusks are more or less evenly distributed from the shore line down to a depth of about 500 feet, but at greater depths their number diminishes rapidly. Within the region down to 500 feet, gastropods are somewhat more conspicuous in the littoral zone (down to 12 feet) and pelecypods at depths of 120 to 210 feet.[46] To this must be added, however, that the great banks of oysters in the north "are usually in 4 or 5 fathoms water; the scallop (*Pecten*) banks at 20 fathoms,"[47] and that pearl fisheries[48] of the south also belong chiefly to the same zone, rarely extending down to 120 feet.

Allee[49] reports that under favorable circumstances the pelecypod *Modiola modiolus* may be so abundant in the littoral zone as to cover the whole bottom with a layer of living mollusks. It appears, therefore, that gregarious pelecypods prefer waters down to a depth of 120 feet.

Appellöf cites abundant burrowing pelecypods in the clayey and sandy bottoms of the area between the shore and the 130-foot mark.

The quoted data are not at variance with the general position of the gastropods and pelecypods, including especially the burrowing pelecypods (*Allorisma*, *Pinna*), in the Big Blue cycles.

ALGAE

The general conclusion of Forbes concerning predominance of leathery sea-weeds to a depth of 90 feet, and the common occurrence of calcareous

[45] Edward Forbes: *Report on the mollusks and Radiata of the Aegean Sea, and on their distribution as bearing on geology*, Brit. Assoc. Adv. Sci., 13th Rept. (1844) p. 130-193.

[46] *Op. cit.*, p. 169-171.

[47] S. P. Woodward: *Manual of the Mollusca* (1858) p. 8.

[48] G. W. Tryon: *Structural and systematic conchology* (1882) p. 176.

[49] W. C. Allee: *Organization of marine coastal communities*, Univ. Chic., Ecol., Mon., vol. 4 (1934) p. 547.

sea-weeds (encrusting *Lithothamnium* and branching *Corallina*) below this depth, have already been mentioned. To this may be added the fact that the vertical distribution of the lime-secreting algae is known to extend to somewhat greater depths than that of the reef-building corals, but ordinarily it is limited to about 200 feet.[50]

The encrusting structures suggestive of lime-secreting red algae of the *Lithothamnium* type are occasionally found in the Big Blue series and are common in the underlying Pennsylvanian rocks of Kansas. They are found in association with pelecypods, brachiopods, and some even with fusulinids. The impressions of leathery sea-weeds have been observed only in the pelecypod(4) and *Lingula*(3) phases of the Big Blue cycles. This occurrence of leathery and calcareous algae in the Big Blue sediments compares well with the general distribution of this marine vegetation in modern seas.

SIGNIFICANCE OF CYCLIC SEDIMENTATION

GENERAL FACTORS

Although character of sea bottom, temperature, salinity, food supply, and other factors of environment undoubtedly influenced the distribution of marine organisms during Big Blue time, periodic change of sea level was probably the main factor producing the cyclic recurrence of stratigraphic units. The gentle sea-level oscillations that accompanied epeirogenic pulsations of the continents are quite sufficient to produce the observed faunal and lithologic changes. Gradual subsidence of the whole Mid-Continent platform under weight of accumulating sediments must have been taking place according to laws of isostasy, but, as this could counterbalance only a fraction of the thickness of cyclic sediments, the combination of accumulation and isostatic subsidence evidently cannot alone explain the symmetrical sedimentary cycles in the Big Blue series. They should have contributed, however, to fluctuations of the sea. Greater sinking than that possibly due to compensating isostatic movements could have been developed through general nonisostatic epeirogenic subsidence of local portions of the crust. However, mere accumulation of sediments could not have produced complete emergence between two cyclic marine transgressions, because the thickness of sediments of a single marine cycle averages 50 feet and, therefore, is not sufficient to fill depths of 160 to 180 feet, which depths are indicated by the biota of the deepest phases of the cycles. Comparison of the zonal distribution of living marine organisms with the cyclic distribution of the fossils in the sediments of the Permian rocks of Kansas indicates that the maxi-

[50] W. H. Twenhofel: *Treatise on sedimentation*, 2d ed. (1932) p. 307.

mum cyclic subsidence of the Late Paleozoic sea of Kansas amounted to about 180 feet.

If it were possible that the maximum depth of deposition in Big Blue time in Kansas was one-half or one-third as shallow as 180 feet, the depth at which fusulinids and other invertebrates of the deepest phases lived must have been 90 feet or less, which is much shallower than the zone of most of the recent articulate brachiopods, as summarized by Schuchert.[51] Environmental factors other than depth of water, unless these are definitely related to depth, produce effects other than those observed in the most typical and complete sedimentary cycles under discussion.

INFLUENCE OF SALINITY

Considerable changes in salinity, such as are observed in estuaries where water is greatly freshened by rivers, or in lagoons where great salinity is due to excessive evaporation, produce noticeable changes in the bottom faunas. These changes are recognized, for example, in Carboniferous and Permian sediments in which the cycles of deposition under discussion are observed. The so-called non-marine pelecypods, which are always found in closed communities, and occasionally in association with other organisms (*Lingula* and others) that indicate unusual degree of freshness of water, or, on the contrary, of great salinity, exemplify the influence of character of water. Moderate changes in salinity are associated with other factors such as depth, clearness of water, and penetration of light, to produce the environments that form successive zones paralleling the shore.

Observations by Appellöf, Forbes, and others clearly indicate that some other factors have greater effect upon the bottom dwellers of the shallow belts than moderate changes in salinity have. Although changes in salinity are more pronounced toward the shore line, here, other influences, such as character of bottom and currents, also become stronger.

The great variation of all these factors is characteristic of the near-shore environments. It results partly in separation of different organisms into communities that are adapted to different portions of the near-shore belts, and, in part, it results in adaptation of all organisms of a belt to those changes that are periodic and affect equally the whole belt. Most pronounced is the rise and fall of water in the tidal zone. According to Appellöf, changes in salinity as well as temperature are periodic at depths down to 30 or 40 meters. Insofar as analysis of the discussed cycles is concerned, it is noteworthy that each recognized phase of the sedimentary cycles in Kansas is remarkably uniform both in

[51] Charles Schuchert: *Paleogeographic and geologic significance of recent Brachiopoda*, Geol. Soc. Am., Bull., vol. 22 (1911) p. 258-275.

organic and in lithologic content. This indicates that there was little or no differentiation into facies within the zones or belts defined by the sediments that make up these phases.

INFLUENCE OF TEMPERATURE AND LIGHT

The influence of temperature and light are well known and need not be here discussed. It suffices to say that changes in both temperature and light are intimately connected with change of depth.

PHYSICAL CHARACTER OF BOTTOM

The shallow-bottom life in modern seas is arranged in belts more or less parallel to the shore line, but differences in the physical character of the bottom result in separation of communities within each belt, particularly in the shallowest ones. Only insignificant, if any, changes of that sort can be observed along the outcrops of the Big Blue rocks, probably because no clastic sediments other than fine muds, silts, and some fine sand were deposited on the floor of the Big Blue sea in Kansas.

It is interesting to observe that a change from clayey to calcareous bottom in the advancing sea and a reverse change from calcareous to clayey bottom in the regressing sea apparently resulted in slight differences in faunal content in the corresponding phases of the progressive and regressive hemicycles, creating a certain asymmetry of the otherwise symmetrical cycles of the Big Blue. For instance, the observed abundance of gastropods other than bellerophontids in the molluscan phase of regressive hemicycles and the rarity or absence in the corresponding phase of progressive hemicycles may be due to the difference in character of the bottom in the progressive and regressive hemicycles.

CORRESPONDENCE OF BIG BLUE PHASES TO ZONES IN SHALLOW MODERN SEAS

FOSSIL-BEARING PHASES

Comparison of the general distribution of benthonic organisms in modern seas with the succession of faunal phases in the Big Blue cycles suggests clearly the possibility of interpreting the latter in terms of depth of deposition. This interpretation is based on two assumptions:

1. The classes of marine animals and plants of Late Paleozoic time lived largely in the same environments as the corresponding classes of organisms today. The order of succession of these organisms in the Big Blue sedimentary cycles, as well as in other Late Paleozoic cycles elsewhere in the world, strongly supports this conclusion.

2. The distribution of benthonic organisms in the Big Blue sea was controlled chiefly by changes in relative depth of sea level.

The first of these two assumptions may be criticised on the ground that there is lack of absolute proof that extinct animals and plants lived in about the same environments as the corresponding modern classes of organisms. Most naturalists agree, however, that unless the principle that "the present is the key to the past" is accepted, there is little on which to base an approach to the problem of environments of organisms of the past. Checking the probable environments in which certain extinct organisms lived by evidence supplied by associated organic remains (and by lithology) is recommended by many prominent paleontologists (Stanton,[52] Neaversen,[53] and others). Such check for the case here discussed is provided by abundant marine animal and plant remains of varied sorts in the Big Blue series.

The chief evidence in support of the second assumption is the remarkable similarity between the order of succession of faunal phases in each sedimentary cycle of the Big Blue series and the order of succession of marine life zones defined by depth of water in modern seas.

The influence of physical character of the bottom, which considerably affects distribution of organisms in modern seas, apparently can be neglected in considering the Big Blue sedimentary cycles, because the bottom of the Big Blue seas must have been very uniform in physical character within each zone of depth. Undoubtedly, these uniform conditions must have tended to minimize, if not to eliminate, possible fluctuations of temperature (other than daily or seasonal changes which affected the whole region), salinity, and clearness of water, within each belt of depth that produced a distinguishable phase in the Big Blue cycles.

In 1911, on the base of various data, E. O. Ulrich concluded that "the average depth of the Paleozoic continental seas [of North America] were less than 200 feet, and that none attained depths exceeding 100 fathoms." [54]

In 1929, when discussing the environment of Pennsylvanian life in North America and particularly in the northern Mid-Continent, R. C. Moore concluded that the depths of the Pennsylvanian epi-continental seas "were possibly, in fact probably, almost nowhere so much as 100 fathoms," that the sea "may be conceived to have been always shallow," and that they "were not only very shallow but they were excessively fluctuating." [55] It now appears that the sea that covered Kansas and adjacent territory in Late Paleozoic time was not deeper than about 200 feet.

[52] T. W. Stanton: *The significance of ammonites in interpreting depth and temperature of the waters in which they lived*, unpublished manuscript quoted by W. H. Twenhofel: *Treatise on sedimentation*, 2d ed. (1932) p. 179.

[53] Ernest Neaversen: *Stratigraphical paleontology* (1928) p. 89, 90. Macmillan and Co., London.

[54] E. O. Ulrich: *Revision of the Paleozoic systems*, Geol. Soc. Am., Bull., vol. 22 (1911) p. 362.

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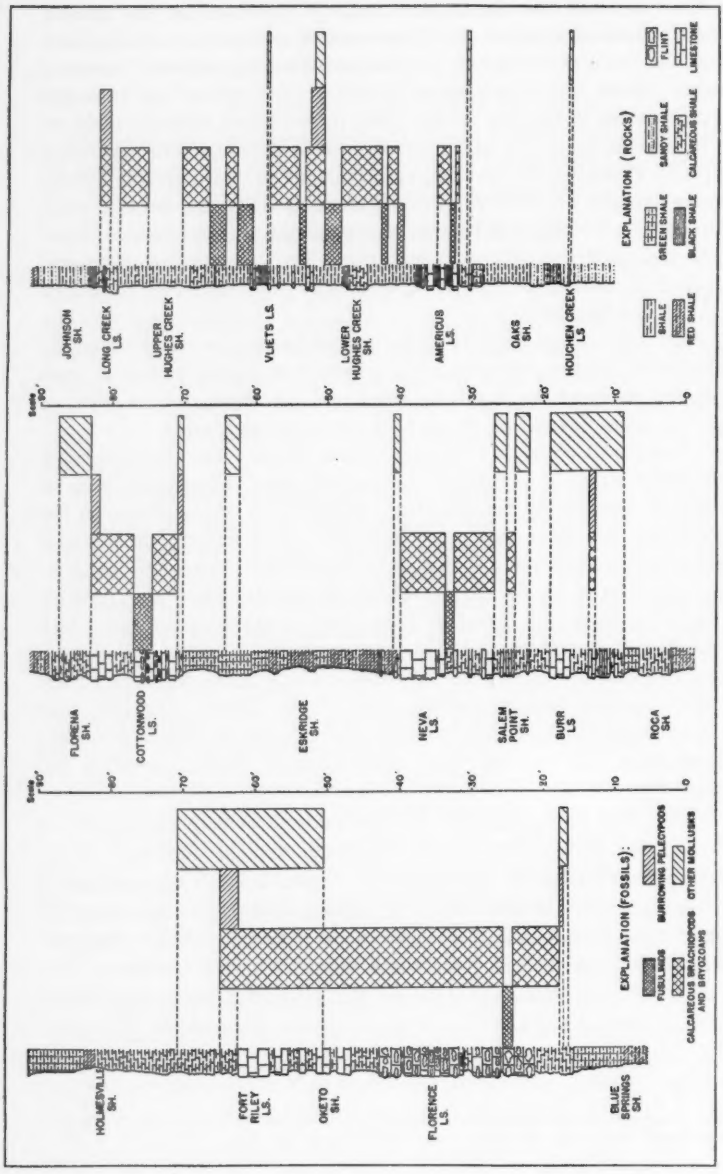

FIGURE 4.—*Detailed sections and phase thicknesses*

Illustrating the most complete sedimentary cycles of the Big Blue series and showing comparative thickness of the phases differentiated by their fossil content.

The main evidence for this conclusion is the position of fusulinids in cycles of the Big Blue, which indicates that they belong to the deepest bottoms. Inasmuch as the modern larger benthonic Foraminifera live in waters under 180 feet, this depth is selected as probably the deepest at which the Big Blue fusulinids lived (Fig. 3 B). This selection seems to be supported by the following observations. In some fusulinid facies from the Virgil series, which underlies the Big Blue beds, encrusting calcareous structures referable to *Osagia* have been observed (in the upper fusulinid phase of the lower Oread, in the fusulinid phase of the lower Deer Creek, in the Tarkio fusulinid limestone). Although these presumably algal incrustations are rather rare in the listed phases, their appearance within the fusulinid zones suggests a depth of 180 feet or shallower, because, below this depth, photosynthetic processes essential for chlorophyll-containing algae are considered practically impossible, even in the clearest waters. The very existence of the modern larger fusulinids is thought to be dependent on the particular commensal algae, and, thus, the distribution of these algae also delimits the depth at which these Foraminifera live.

Another basis for selection of the 180-foot depth is provided in the fact that next to the fusulinid (7) phase in the cycles of the Big Blue is the prominent phase (6) of calcareous brachiopods, bryozoans, and corals, a combination suggestive of depths between 90 and 150 feet. Furthermore, in the Americus, lower Oread, and other cycles, burrowing pelecypods have been observed in the fusulinid phase.

Intimately interbedded phases 7 and 6, as in the Foraker cycle of the Big Blue series or in the upper Oread cycle (Plattsmouth cycle of the Oread megacycle) of the Virgil series, suggest the proximity of the fusulinid and brachiopod zones in the Late Paleozoic seas, because the repeated change from one phase to another within a single cycle is much more easily explained as due to slight changes of ocean water level (or some other subtle changes of environment) than as being a result of rapidly repeated considerable changes of sea level, which shifted the depth from a much shallower brachiopod-bryozoan-coral environment to a much deeper fusulinid environment several times within what seems to be a single marine invasion (Fig. 1C).

The critical 90-foot depth, below which the most modern articulate or calcareous brachiopods live, is inferred to correspond to the line of division between the mixed fauna (5) phase of the Big Blue, with its abundant calcareous brachiopods, and the molluscan (4) phase, in which calcareous brachiopods are rare. The 60-foot depth is selected to mark the contact of the *Lingula* (3) and the molluscan (4) phases in the cycle of the Big

Blue, because this corresponds to the deepest occurrence of modern *Lingula*. The division of the deeper waters of the Big Blue sea (from 90 to 180 feet) between the 7 and 6 + 5 phases is made on the ground of the relative thickness of these phases. In so doing the following assumptions are made:

1. The advance and retreat of the sea, which resulted in deposition of the observed sedimentary cycles, were, on the average, of the same rate throughout the cycles.

2. The rate of deposition of the largely calcareous sediments of the brachiopod and fusulinid phases was generally the same.

Comparison of the thickness of 7 and 6 + 5 phases in the four most complete cycles of the Big Blue series (Foraker, Grenola, Beattie, and Barneston) permits the conclusion that phases 6 + 5, on the average, are about two to four times as large as phase 7 (Fig. 4). Inasmuch as the thin fusulinid (7) phases of the Grenola and the Barneston cycles may, and probably do, represent only a fraction of a complete deep phase, which here did not develop in full or to a depth of 180 feet, the larger proportion of phase 7 to phases 6 + 5, or a proportion of 1 to 3½, is selected to represent the more likely proportional subdivision of 90 to 180 feet depth between the corresponding zones. Thus, the brachiopod (6) and the mixed (5) zones are thought to stretch from a depth of 90 to 160 feet and the fusulinid (7) zone from 160 to 180 feet. It is interesting to note that King reports that calcareous brachiopods with thinner shell, indicative of deeper water, are found together with radiolarians in some Late Paleozoic sediments of Texas (Leonard formation), and these apparently belong to a deeper phase than that indicated by fusulinids. The depth of 150 feet corresponds, also, as has already been pointed out, to the depth down to which most modern corals are distributed, which thus corresponds approximately to the occurrence of corals in the Big Blue (as well as in the earlier Pennsylvanian) cycles.

RED AND GREEN BEDS

The change from green to red silt, at the shallow end of the Big Blue cycle, is interpreted to indicate the upper limit of the zone of tides. The development of 30 or 40 feet of red shale was probably subaerial and most probably represents combined wind and water transfer of the red soil developed on somewhat higher land. In the Big Blue cycles there is, as a rule, a green shale phase, which is about as thick as the red shale phase and in places contains *Lingula* in the part adjacent to pelecypod phase. The change from red to green shale is marked in many places by interbedding, by a zone of mottled red and green shale, or by beds that change from duller red, maroon to purple, to dark blue-green. The more earthy colors of these shales seem to be due not to fine-grained

glauconite, but to the reducing action of organic matter upon iron oxides of the original red silt. The common observation of a greenish halo around organic remains embedded in reddish sediments is the best illustration of this process. The alternate submergence and emergence of the zone of tides seems to be favorable for rapid oxidation of the dead organic remains, but their well-known great accumulation in this zone seems to be responsible for reducing action in the zone, as pointed out by Twenhofel.[56] Therefore, the zone of tides is included in the area in which reduction of the red to green silt has taken place. The change from predominantly red to largely green is thus selected as indicating the upper limits of deposition in the zone of tides. The change from the molluscan (4) to *Lingula* (3) phase is chosen as corresponding to 60-foot depth, down to which lives, according to Schuchert, modern *Lingula*. The boundary between the *Lingula* (3) phase and the unfossiliferous green shale (2) is arbitrarily concluded to indicate deposition at a depth of about 30 feet.

CYCLES AND DEPTH OF DEPOSITION IN THE PENNSYLVANIAN SEA

A cyclic succession of faunal zones similar to that in the Big Blue series is observed throughout the Pennsylvanian rocks of Kansas and adjacent territory. In these cycles the fusulinid phase also is in a central position and is flanked above and below by the brachiopod-bryozoan-coral phase. Most of the sedimentary cycles in these rocks are less regular than in the Big Blue series, which may have been due to less even bottom conditions, greater influence of current and wave action, and other possible factors that interfered with the control provided by depth of deposition. Owing to influence of one or more of these factors at any particular time and place, the normal position in a cycle of various benthonic organisms (as detected in the Big Blue series) may be somewhat shifted up or down outside of the depths which they normally occupied. In view of all this, it seems reasonable to conclude that the maximum depth of the Pennsylvanian sea in eastern Kansas, also determined by the presence of the deepest fusulinid phase, was about 200 feet. In the western part of the State the depth was probably slightly greater, as this area was farther away from the shore line.

CONCLUSIONS

In the Big Blue series of Kansas the following cyclic succession is observed: (1) red shale, (2) green shale, (3) *Lingula* phase, (4) molluscan phase, (5) mixed fauna (molluscan and brachiopod) phase, (6) brachiopod phase, (7) fusulinid phase; after which the same phases appear in

[56] Letter of January 7, 1936.

reverse order until the red shale phase is again reached. Bryozoans and corals are restricted to phases 5 and 6; burrowing pelecypods are most prominent in phase 5 but appear also in phases 6 and 7. Leathery seaweeds have been found in phases 3 and 4 and calcareous algal incrustations in phases 4 and 5 (also in 6 and 7 in the Pennsylvanian rocks below the Big Blue). Comparison of distribution of organisms in the cycles of the Big Blue with the benthonic zones of modern seas suggests the following:

1. The various classes of marine organisms in Late Paleozoic time were adapted to about the same environments as they are today.
2. Observed cyclic repetition of sedimentary rocks and the enclosed organic remains indicate advance and retreat of sea, each cycle representing one major marine invasion.
3. Red shales that separate marine phases of two neighboring cycles are continental deposits and indicate emergence.
4. Maximum depth of the Big Blue sea did not exceed 180 feet, and the depth of the earlier Pennsylvanian sea in Kansas probably did not exceed 200 feet.
5. The Late Paleozoic benthonic organisms that characterize the phases of the Big Blue cycles were adapted to the following approximate depths: fusulinids, from 160 to 180 feet; calcareous brachiopods, from 90 to 160 feet; corals, from 90 to 140 feet; bryozoans, from 75 to 160 feet; burrowing pelecypods, from 90 to 180 feet; other pelecypods, from 60 to 110 feet; and leathery sea-weeds, from 30 (or probably from shore line) to 75 feet.

Although the suggested ranges of depths which the different Late Paleozoic benthonic organisms occupied are selected in a somewhat arbitrary way, it appears that these depths, expressed in round figures, approximate the actual depths of the benthonic zones of Late Paleozoic seas.

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